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ABC Dirt/Soil Scientists, Seattle, WA

Prepared for

Municipal Environmental Research Lab.
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SOIL PROPERTIES, CLASSIFICATION, AND HYDRAULIC CONDUCTIVITY TESTING

Draft Technical Resource Document
for Public Comment

(SW-925)

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

OFFICE OF SOLID WASTE AND EMERGENCY RESPONSE
U.S. ENVIRONMENTAL PROTECTION AGENCY
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March 1984

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DISCLAIMER

This report was prepared by D. W. Roberts of ABCDirt/Soil Scientists, Seattle, Washington, under Contracts 68-03-2933 and 68-03-3068. The EPA Project Officer was M. H. Roulier of the Municipal Environmental Research Laboratory, Cincinnati, Ohio.

This is a draft report that is being released by EPA for public comment on the accuracy and usefulness of the information in it. The report has received extensive technical review but the Agency's peer and administrative review process has not yet been completed. Therefore it does not necessarily reflect the views or policies of the Agency. Mention of trade names or commercial products does not constitute endorsement or recommendtion for use.

FOREWARD

The Environmental Protection Agency was created because of increasing public and governmental concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of the environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is the first necessary step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and the solid and hazardous waste pollutant discharges from municipal and community sources; to preserve and treat public drinking water supplies; and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research--a vital communications link between the researcher and the user community.

This Technical Resource Document (TRD) is a compilation of available laboratory and field testing methods for the measurement of hydraulic conductivity (permeability) of soils along with background information on relevant soil properties and classification systems. The TRD was developed to assist those involved in planning and construction of hazardous waste disposal facilities and to support the Technical Guidance Documents and Permit Guidance documents issued by EPA to assist preparers and reviewers of applications for permits under Subtitle C of the Resource Conservation and Recovery Act (RCRA). This document is intended to supplement, and not replace, the Technical Resource Document entitled, "Method 9100: Saturated Hydraulic Conductivity, Saturated Leachate Conductivity, and Intrinsic Permeability."

Francis T. Mayo, Director
Municipal Environmental
Research Laboratory

PREFACE

Subtitle C of the Resource Conservation and Recovery Act (RCRA) requires the Environmental Protection Agency (EPA) to establish a Federal hazardous waste management program. This program must ensure that hazardous wastes are handled safely from generation until final disposition. EPA issued a series of hazardous waste regulations under Subtitle C of RCRA that is published in 40 Code of Federal Regulations (CFR) 260 through 265 and 122 through 124.

Parts 264 and 265 of 40 CFR contain standards applicable to owners and operators of all facilities that treat, store, or dispose of hazardous wastes. Wastes are identified or listed as hazardous under 40 CFR Part 261. The Part 264 standards are implemented through permits issued by authorized states or the EPA in accordance with 40 CFR Part 122 and Part 124 regulations. Land treatment, storage and disposal (LTSD) regulations in 40 CFR Part 264 issued on July 26, 1982, establish performance standards for hazardous waste landfills, surface impoundments, land treatment units, and waste piles.

The Environmental Protection Agency is developing three types of documents for preparers and reviewers of permit applications for hazardous waste LTSD facilities. These types include RCRA Technical Guidance Documents, Permit Guidance Manuals, and Technical Resource Documents (TRD's). The RCRA Technical Guidance Documents present design and operating specifications or design evaluation techniques that generally comply with or demonstrate compliance with the Design and Operating Requirements and the Closure and Post-Closure Requirements of Part 264. The Permit Guidance Manuals are being developed to describe the permit application information the Agency seeks and to provide guidance to applicants and permit writers in addressing the information requirements. These manuals will include a discussion of each step in the permitting process, and a description of each set of specifications that must be considered for inclusion in the permit.

The Technical Resource Documents present state-of-the-art summaries of technologies and evaluation techniques determined by the Agency to constitute good engineering designs, practices, and procedures. They support the RCRA Technical

Guidance Documents and Permit Guidance Manuals in certain areas (i.e., liners, leachate management, closure covers, water balance) by describing current technologies and methods for designing hazardous waste facilities or for evaluating the performance of a facility design. Although emphasis is given to hazardous waste facilities, the information presented in these TRD's may be used in designing and operating non-hazardous waste LTSD facilities as well. Whereas the RCRA Technical Guidance Documents and Permit Guidance Manuals are directly related to the regulations, the information in these TRD's covers a broader perspective and should not be used to interpret the requirements of the regulations.

This document is a first edition draft being made available for public review and comment. It has undergone review by recognized experts in the technical areas covered, but Agency peer review processing has not been completed yet. Public comment is desired on the accuracy and usefulness of the information presented in this manual. Comments received will be evaluated, and suggestions for improvement will be incorporated, wherever feasible, before publication of the second edition. Communications should be addressed to Docket Clerk, Room S-212(A), Office of Solid Waste (WH-562), U.S. Environmental Protection Agency, 401 M Street, S.W., Washington, D.C., 20460. The document under discussion should be identified by title and number; e.g., "Soil Properties, Classification, and Hydraulic Conductivity Testing (SW-925).

ABSTRACT

This Technical Resource Document (TRD) is a compilation of available laboratory and field testing methods for the measurement of hydraulic conductivity (permeability) of soils along with background information on relevant soil properties and classification systems. This TRD was developed to assist those involved in planning and construction of hazardous waste disposal facilities and also supports the Technical Guidance Documents and Permit Guidance Documents issued by EPA to assist reviewers of application for permits under Subtitle C of the Resource Conservation and Recovery Act (RCRA).

The review of the literature consisted of searches through the National Technical Information Service network and several professional data bases available through the University of Washington. Technical reports were also obtained from the EPA Region X library, and some documents and recommended readings forwarded to us by colleagues.

Background information on soil classification, soil water, and soil compaction are included along with descriptions of sixteen methods (laboratory and field) for determination of saturated or unsaturated hydraulic conductivity.

The conclusions that can be drawn from this study are: (1) The area of soil testing for hydraulic conductivity overlaps several professions: geology, hydrology, soil engineering, and soil science; (2) Most testing methods for hydraulic conductivity have been developed for agricultural or engineering purposes other than application to the feasibility and design of solid or hazardous waste disposal sites; (3) All laboratory tests suffer from possible misrepresentation of field conditions due to sample disruption and small size; (4) Most field tests are more applicable to situations of coarse-textured soils rather than fine-grained soils that are more appropriate for disposal sites; (5) It is difficult at this time to discern the degree of variation in soil testing results caused by variation inherent in the soil testing method or by variation of spatial properties of the soils; and (6) Determination of soil hydraulic conductivity values is the limiting factor to further development of the applicability of the saturated-unsaturated transport model.

This report was submitted in fulfillment of Contracts 68-03-2933 and 68-03-3068 by ABCDirt, Inc. under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period from January 30, 1981 to June 15, 1982.

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SECTION 1
INTRODUCTION

In what seems an inevitable progression from an initial demand for goods and services, there follows the extraction of natural resources, production, consumption, and ultimately, the disposal of residuals. While at many points in this progression methods may be used which either reduce the overall quantity or change the form of waste materials, the capacity of the environment to assimilate final residuals is finite. The quality of human life can be impaired when such capacity is exceeded.

Any assessment of the capacity of the environment to immobilize, attenuate, or transport applied waste materials must consider the rate of water and/or pollutant movement through soils regardless of whether the wastes are applied onto or injected into the surface soil, or the wastes are placed into lined surface impoundments or buried in lined landfills. Presently, there are not recognized U.S.A. standards for determining the rate of water and/or pollutant movement in fine-textured soils which are more desirable for waste disposal facilities. This Technical Resource Document (TRD) is intended to provide information and guidance on available soil testing methods that are presently in use by scientists and engineers to determine the rate of water and/or pollutant movement in soils.

It should be noted that this TRD provides information on a variety of methods without identifying a preferred method. Recommended methods are described in the Technical Guidance Documents and Permit Guidance Documents issued by EPA to assist preparers and reviewers of applications for permits under Subtitle C of the Resource Conservation and Recovery Act (RCRA). See the Preface of this TRD (pages iv and v) for further information on these two documents. The EPA publication entitled "Test Methods for Evaluating Solid Waste: Physical and Chemical Methods (SW-846) also describes a recommended method (#9100) for measuring hydraulic conductivity. Permit applicants may use other methods but must demonstrate that they are appropriate for the specific circumstances. This TRD is one source of information for applicants who are considering use of other methods.

While there is much discussion and disagreement regarding the use of the terms hydraulic conductivity versus permeability, hydraulic conductivity is preferentially used in this text and is defined as the flux of water per unit gradient of hydraulic potential and is the proportionality factor in Darcy's Law whereas permeability refers to the ease with which gases, plant roots, or water pass through a bulk mass of soil. In general usage, these two terms are used interchangeably. It can be noted that hydraulic conductivity is the most variable property of soil with a range in values exceeding fourteen orders of magnitude (Cedergren, 1977).

While the TRD is principally written for use in connection with hazardous waste land treatment, surface impoundments, and landfill facilities; it can also be applied to other types of landbased waste disposal systems where soil testing methods for hydraulic conductivity are needed, such as: non-hazardous waste landfills and surface impoundments, land treatment (landfarming), land application of domestic wastewater, and on-site sewage disposal systems.

Section 2 provides background information on how soils are classified by soil scientists according to how soils are formed and exist in the natural landscape, and by soil engineers according to the physical properties of a soil material.

Section 3 provides a wide variety of informtion on factors of the soil that affect water relations and movement. Darcy's Law concerning the rate of liquid movement through a porous medium is discussed, along with factors that affect such movement through soils such as soil pore geometry, anisotropy, and permeant. A general discussion of the types of errors associated with testing for hydraulic conductivity is also introduced.

Section 4 describes the relevant parameters of soil compaction and how compaction relates to hydraulic conductivity. One subsection also discusses the errors commonly involved in testing the hydraulic conductivity of compacted soil samples.

Section 5 provides a discussion of the types of water movement flow regimes that are relevant to the different kinds of waste disposal facilities used for hazardous waste disposal such as land treatment, landfills, or surface impoundments.

Actual soil testing methods and procedures for determination of hydraulic conductivity are described for both saturated and unsaturated liquid flow in Section 6. It should be noted that most of the test methods use water, rather than a waste liquid, as the permeant.

In Section 7, important considerations and limitations of laboratory and field testing methods are summarized. A soil testing methods matrix is presented which offers information for each method on: application to specific type of problem/facility, precision and accuracy, limitations of test, status of the method, and comments.

A glossary of technical soil terms used in the text is provided as an appendix.

SECTION 2

SOIL CLASSIFICATION

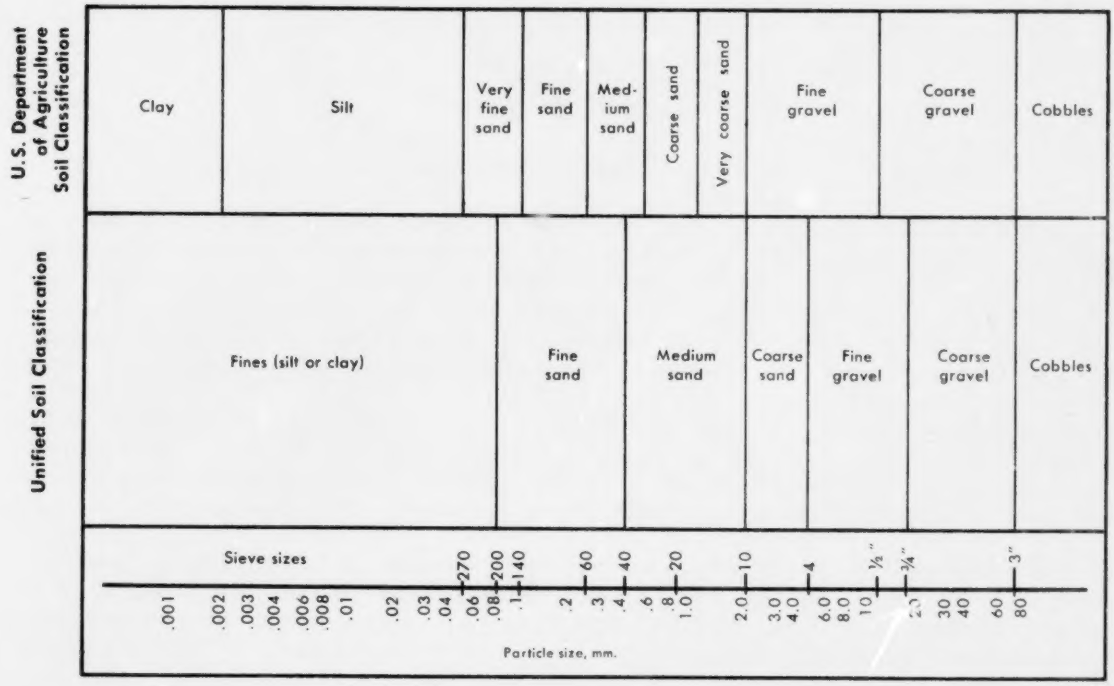
In current use in the United States there are two major schemes for classifying soils for purposes of evaluation and design of hazardous waste land disposal sites. One classification scheme (used by the U.S. Department of Agriculture (USDA), Soil Conservation Service and other Professional Soil Scientists) is a system based on quantitatively measurable physical and chemical properties as they exist in the field. This system's development, since the early 1900's, has occurred alongside soil mapping efforts that have yielded Soil Survey Reports for most U.S. Counties. Such information is used in resource management, land use planning, the agriculture sciences, and forestry.

The second classification scheme is the Unified Soil Classification System (USCS) which was developed after WWII and is a system based on the grain (particle) size and response to physical manipulation at various water contents. This system serves engineering uses of soil in developing dams, roads, liners, etc. Therefore, on a general level, the difference between the two classification schemes is that the USDA system is concerned with mapping of native soil bodies as they occur on the landscape while the USCS system is concerned with the uses of soil as a material and how it will react to outside forces.

Another point regarding the USCS and USDA systems is that both systems may use the same term but have different meanings. The most apparent example of this phenomenon is the difference in the range of particle size classes for the particular soil separates and subclasses of the two systems. This is shown graphically in Table 2-1.

However, even though texture is an important soil property that affects and influences other soil properties, its degree of importance to soil classificaton is different for the two systems. Soil texture is a major criterion in the USCS while it is a minor criterion for classification in the USDA system.

TABLE 2-1 COMPARISON OF PARTICLE SIZE FOR USDA AND UNIFIED SYSTEM



2.1 SOIL TAXONOMY

The soil classification system currently utilized by soil scientists and agronomists to map the areal extent of native soil bodies is called Soil Taxonomy (USDA, 1975). One of the attributes of this system is that the primary elements for discerning different classes in the system are the quantitative physical and chemical properties of soils as they are found in the field. Another attribute of this system is the nomenclature used which is similar to other taxonomic classification schemes as used in other natural sciences such as biology or zoology. The names in Soil Taxonomy (especially for the broader classification categories) give a definite connotation of the major characteristics of the soils in question which can be understood in many languages since Latin or Greek words are the basis for the names.

The characteristics of the soil in any place are a result of the combined influence of climate and living organisms on a specific kind of parent material, conditioned by relief, over a period of time. The combined effect of these factors is reflected in most soils as soil horizons of unique kinds. Each key soil horizon has a unique morphology that reflects its genesis and composition and a unique behavior due to its physical and chemical properties (Bartelli, 1977). The presence or absence of kinds of soil horizons is an important criteria in the classification of soils by Soil Taxonomy (USDA, 1975).

A soil horizon is a layer that has some set of properties that have been produced by soil-forming processes. It also has some properties that distinguish it from the horizons just above and below it. A soil horizon is usually differentiated in the field by characteristics such as texture, structure, consistence, color or other physical or chemical properties.

Diagnostic Horizons

Diagonostic horizons are used in Soil Taxonomy to differentiate soil classes or categories. Surface diagnostic horizons are called epipedons (Greek epi means over, pedon means soil) which includes the upper part of the soil profile darkened by organic matter, the upper eluvial horizons, or both. Six epipedons are recognized as well as six subsurface horizons which are shown in Table 2-2 along with their major features.

TABLE 2-2 MAJOR FEATURES OF DIAGNOSTIC HORIZONS USED TO DIFFERENTIATE AT THE HIGHER LEVELS OF THE USDA CLASSIFICATION SCHEME

Diagnostic Horizon	Major Features
	Surface Horizons(Epipedons)
Mollic	Thick, dark-colored, high-base saturation, strong structure
Umbric	Same as Mollic except low-base saturation
Ochric	Light colored, low organic content, may be hard and massive when dry
Histic	Very high in organic content, wet during some part of the year
Anthropic	Cultivated soil layer rich in N, P, K and bases
Plaggen	Manmade surface layer more than 20 in. thick caused by continuous manuring
	Subsurface Horizons
Argillic	Silicate clay accumulation
Natric	Argillic, high in sodium, columnar or prismatic structure
Spodic	Organic matter, Fe and Al oxide accumulation
Cambic	Changed or altered by physical movements or by chemical reactions
Agric	Organic and clay accumulation just below the plow layer
Oxic	Primarily mixture of Fe, Al oxides, and 1:1-type minerals

Soil Taxonomy is a six-category system that permits aggregation of soil data and interpretations at various levels of generalization, whether they are displayed as maps or statistics. It is the only soil classification system with a consistent, systematic nomenclature that indicates location in the system and something about the properties of the soils in each class (Johnson and McClelland, 1977). The six categories are (1) Order (the broadest category); (2) Suborder; (3) Great Group; (4) Subgroup; (5) Family; and (6) Series (the most specific). Currently in the U. S., there are more than 11,000 recognized soil series.

Order

This category is based largely on the morphology of surface and subsurface horizons with soil genesis as an underlying factor. Any given order includes soils whose properties suggest that they are not too dissimilar in their genesis or soil-forming factors. The ten orders are listed below in Table 2-3. Note that all order names have the common ending "sol" from the Latin "solum" meaning soil. A prevalent soil series in the Puget Sound area of Washington is the Alderwood soil (which was glacially derived) and belongs to the Inceptisol soil order.

TABLE 2-3 ORDERS OF SOIL TAXONOMY

Order	Derviation	Formative Element	Description
Alfisols	Meaningless syllable	alf	Gray to brown epipedons; formed mostly in humid-region areas under native deciduous forests
Aridisols	L. "aridus", dry	id	Desert or dry soils with an ochric epipedon
Entisols	Meaningless syllable	ent	Recent soils lacking profile development; found under wide variety of climatic conditions
Histosols	Gk. "histos", tissue	ist	Organic soils
Inceptisols	L. "inceptum", beginning	ept	Young soils, more developed than Entisols
Mollisols	L. "mollis", soft	oll	Dark (mollic) epipedons, includes some of the world's most important agricultural soils
Oxisols	F. "oxide", oxide	ox	Oxic subsurface horizon from intense leaching of silica leaving Fe and Al oxides
Spodosols	Gk. "spodos", wood ash	od	Light colored (usually albic) horizon above spodic horizon
Ultisols	L. "ultimus", last	ult	Old, moist soils developed under warm to tropical climates, argillic horizons with low base saturation
Vertisols	L. "verto", turn	ert	High content of swelling clays which can develop deep, wide cracks when dry

Suborders

The suborder category within each order emphasize genetic homogeneity. Thus, wetness, climatic environment, and vegetation are characteristics which help determine the suborder in which a given soil is found. The names of suborders are obtained by adding a prefix syllable to a formative element taken from that order name. The suborder for the Alderwood soil series mentioned previously is an ochrept, meaning a light colored ("ochr") young soil ("ept").

Great Groups

The great groups are subdivisons of the suborders based on kind and arrangement of diagnostic horizons or uses of the epipedon. The great groups are named by prefixing the suborder names by an additional descriptive syllable. Again for the Alderwood series, which belongs to the Durochrept great group, it is a light colored, young soil with a hardpan ("dur") subsurface horizon which was formed due to the pressure of glacial ice.

Subgroups

Each great group can be divided into three subgroups: the central (typic) concept of the great groups; the intergrades, or transitional forms to other great groups; and the extragrades, which have some properties that are representative of the great groups but do not indicate transitions to any other known kind of soil. Each subgroup is identified by one or more adjectives preceding the name of the great group. The Alderwood soil is a Dystric Entic Durochrept which means it is a durochrept with low base saturation ("dystr") and recently developed ("ent").

Soil Family

The intent of this category has been to group soils within a subgroup having similar physical and chemical properties that affect their responses to management and manipulation for use. Families are defined primarily to provide groupings of soils with restricted ranges in:

1) Particle-size distribution in horizons of major biologic activity below the plow depth;
2) Mineralogy of the same horizons considered in naming the particle-size classes;
3) Temperature regime;
4) Thickness of the soil penetrable by roots; and
5) A few other properties that are used in defining some families to produce the needed homogeneity (USDA, 1975).

Thus, the Alderwood soil, which is a loamy-skeletal, mixed, mesic dystric entic durochrept means a family of soils within the subgroup dystric entic durochrept that posseses a particle size class where rock fragments greater than 2 mm make up 35 percent or more by volume (loamy-skeletal), has mixed mineralogy, and is located in a temperate climate (mesic).

Soil Series

A soil series is a group of soils developed from the same kind of parent material, by the same genetic combination of processes, and whose horizons are quite similar in their arrangement and general characteristics. Soils of any one series possess a unique characteristic profile in some way different from other series within the same family. Soil series are usually named after cities, regions, rivers or other local geographic conditions close to the place where the soils were originally defined.

The soil type is a subdivision of the soil series and is named according to the texture of the surface horizon. Therefore, with our example of the Alderwood soil series (which is named after an old town in Washington), the surface texture is gravelly loam.

2.2 UNIFIED SOIL CLASSIFICATION SYSTEM

The Unified Soil Classification System (USCS) serves engineering uses of soils. The criteria for soil types in the system are based on the grain (particle) size and response to physical manipulation at various water contents (Fuller, 1978).

The USCS is based on textural characteristics for those soils with such a small amount of fines that the fines do not affect the behavior. It is based on plasticity-compressibility characteristics for those soils where the fines affect the behavior. The plasticity-compressibility characteristics are evaluated by plotting the plasticity index versus the liquid limit on a standard plasticity chart. The position of the plotted point yields information from which to predict behavior as an engineering construction material (Asphalt Institute, 1969).

The following properties form the basis of USCS soil classification:

1) Percentages of gravel, sand and fines (fraction passing No. 200 sieve).
2) Shape of the grain-size-distribution curve.
3) Plasticity and compressibility characteristics.

Four soil fractions are recognized: cobbles, gravel, sand, and fines (silt or clay). The limiting boundaries between the various fractions are given in Table 2-1.

The soils are divided as (1) coarse-grained soils, (2) fine-grained soils, and (3) highly organic soils. The coarse-grained soils contain 50 percent or less material smaller than the No. 200 sieve, and fine-grained soils contain more than 50 percent material smaller than the No. 200 sieve. Highly organic soils can generally be identified visually. The USCS recognizes 15 soil groups and uses names and letter symbols to distinguish between these groups. These symbols are derived either from the terms descriptive of the soil fractions, their relative value of liquid limit (high or low), or relative gradation (well-graded or poorly graded); and are used to form the group symbols which correspond to the names of typical soils as seen in Table 2-4.

The coarse grained soils are subdivided into gravels (G) and sands (S). The gravels have a greater percentage of the coarse fraction (that portion retained on the No. 200 sieve) retained on the No. 4 sieve, while the sands have the greater portion passing the No. 4 sieve. Both the gravel and sand groups are divided into four secondary groups (Table 2-4).

Fine-grained soils are subdivided into silts (M) and clays (C), depending on their liquid limit and plasticity index. Silts are those fine-grained soils with a liquid limit and plasticity index that plot below the "A" line in Table 2-4, under Laboratory Criteria, while clays are those that plot above the "A" line. Organic clays are the exception to the above rule, as the liquid limits and plasticity indexes of those soils plot below the "A" line. The silt, clay and organic fractions are further subdivided on the basis of relatively low (L) or high (H) liquid limits. The arbitrary dividing line between the low and high liquid limits has been set at 50. Representative soil types for each of these groups (ML, MH, CL, CH, OL, and OH) can be found under the "Typical Names" column in Table 2-4.

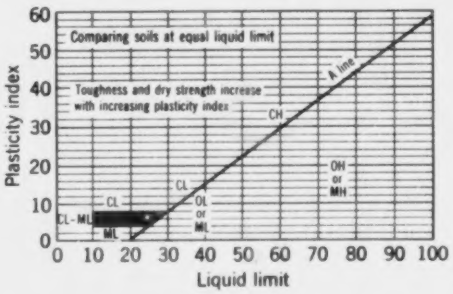
Field Classification

The USCS is designed so that most soils can easily be classified into the three primary groups (coarse-grained, fine-grained, and highly organic) by means of visual inspection and simple field tests. Additionally, with some field experience, classification into the subdivisions can be performed with a considerable degree of success. Further, laboratory tests for classification may be performed to provide greater accuracy and precision and/or as back-up to field-derived information.

The field classification procedure consists of a process of elimination and occurs by moving from left to right in Table 2-4 until the proper group name is obtained. The general procedure followed is described as follows: (1) Obtain a representative sample or the soil; (2) Estimate the size of the largest particle; (3) Remove the boulders and cobbles and estimate the amount (percentage by weight) represented by this fraction in the total sample; (4) Spread the dry sample on a flat surface or in the palm of the hand, and classify as coarse-grained or fine-grained; (5) If coarse-grained, classify as gravel or sand by criteria in Table 2-4; (6) If gravel or sand, classify as "clean" or "with appreciable fines" where fines are the fraction smaller than 0.074 mm (No. 200 sieve); (7) If the gravel or sand is clean, decide if it is well-graded (W) or poorly-graded (P), and assign the appropriate group name (GW, GP, SW, or SP); (8) If the gravel or sand contains appreciable fines, decide if the

TABLE 2-4 UNIFIED SOIL CLASSIFICATION SYSTEM (U.S.C.S.) (LAMBE AND WHITMAN, 1979).

Field Identification Procedures (Excluding particles larger than 75 μm and basing fractions on estimated weights)							Group Symbols[a]	Typical Names	Laboratory Classification Criteria			
Coarse-grained soils More than half of material is *larger* than 75 μm sieve size[b] (The 75 μm sieve size is about the smallest particle visible to naked eye)	Gravels More than half of coarse fraction is larger than 4 mm sieve size	Clean gravels (little or no fines)	Wide range in grain size and substantial amounts of all intermediate particle sizes				*GW*	Well graded gravels, gravel-sand mixtures, little or no fines	Use grain size curve in identifying the fractions as given under field identification	Determine percentages of gravel and sand from grain size curve Depending on percentage of fines (fraction smaller than 75 μm sieve size) coarse grained soils are classified as follows: Less than 5% *GW, GP, SW, SP* More than 12% *GM, GC, SM, SC* 5% to 12% *Borderline* cases requiring use of dual symbols	$C_U = \frac{D_{60}}{D_{10}}$ Greater than 4 $C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			Predominantly one size or a range of sizes with some intermediate sizes missing				*GP*	Poorly graded gravels, gravel-sand mixtures, little or no fines			Not meeting all gradation requirements for *GW*	
		Gravels with fines (appreciable amount of fines)	Nonplastic fines (for identification procedures see *ML* below)				*GM*	Silty gravels, poorly graded gravel-sand-silt mixtures			Atterberg limits below "A" line, or *PI* less than 4	Above "A" line with *PI* between 4 and 7 are *borderline* cases requiring use of dual symbols
			Plastic fines (for identification procedures, see *CL* below)				*GC*	Clayey gravels, poorly graded gravel-sand-clay mixtures			Atterberg limits above "A" line, with *PI* greater than 7	
	Sands More than half of coarse fraction is smaller than 4 mm sieve size	Clean sands (little or no fines)	Wide range in grain sizes and substantial amounts of all intermediate particle sizes				*SW*	Well graded sands, gravelly sands, little or no fines			$C_U = \frac{D_{60}}{D_{10}}$ Greater than 6 $C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			Predominantly one size or a range of sizes with some intermediate sizes missing				*SP*	Poorly graded sands, gravelly sands, little or no fines			Not meeting all gradation requirements for *SW*	
		Sands with fines (appreciable amount of fines)	Nonplastic fines (for identification procedures, see *ML* below)				*SM*	Silty sands, poorly graded sand-silt mixtures			Atterberg limits below "A" line or *PI* less than 5	Above "A" line with *PI* between 4 and 7 are *borderline* cases requiring use of dual symbols
			Plastic fines (for identification procedures, see *CL* below)				*SC*	Clayey sands, poorly graded sand-clay mixtures			Atterberg limits below "A" line with *PI* greater than 7	
Fine-grained soils More than half of material is *smaller* than 75 μm sieve size	Identification Procedures on Fraction Smaller than 380 μm Sieve Size											
				Dry Strength (crushing characteristics)	Dilatancy (reaction to shaking)	Toughness (consistency near plastic limit)						
	Silts and clays liquid limit less than 50			None to slight	Quick to slow	None	*ML*	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity				
				Medium to high	None to very slow	Medium	*CL*	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays				
				Slight to medium	Slow	Slight	*OL*	Organic silts and organic silt-clays of low plasticity				
	Silts and clays liquid limit greater than 50			Slight to medium	Slow to none	Slight to medium	*MH*	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts				
				High to very high	None	High	*CH*	Inorganic clays of high plasticity, fat clays				
				Medium to high	None to very slow	Slight to medium	*OH*	Organic clays of medium to high plasticity				
Highly Organic Soils			Readily identified by colour, odour, spongy feel and frequently by fibrous texture				*Pt*	Peat and other highly organic soils				



Plasticity chart
for laboratory classification of fine grained soils

From Wagner, 1957.

[a] *Boundary classifications.* Soils possessing characteristics of two groups are designated by combinations of group symbols. For example *GW–GC*, well graded gravel-sand mixture with clay binder.

[b] All sieve sizes on this chart are U.S. standard.

fines are silty (M) or clayey (C), and classify as GM, GC, SM, or SC; (9) for fine-grained soils or the fine-grained portion of a coarse-grained soil, the dilatancy (reaction to shaking), the dry strength (crushing characteristics), and toughness (consistency near plastic limit) are performed; (10) Highly organic soils (Pt) are characterized by undecayed particles of leaves, sticks, grass, and other vegetative matter giving the soil a fibrous texture; and (11) Soils which have characteristics of two groups are given boundary classification using a name most nearly describing the soil, and the two group symbols are listed such as GW-GC.

Although the use of letter symbols is convenient, it does not describe a soil as completely as is normally required. Therefore, descriptive terms should be used and arranged in narrative form in addition to the letter symbols to produce a more complete soil classification. Such descriptions differ between coarse-grained and fine-grained soils and are shown below with examples.

> For Coarse-grained soils: Give typical name; indicate approximate percentages of sand and gravel, maximum size; angularity, surface condition, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information; and symbol in parentheses. For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions and drainage characteristics.
>
> Example: Silty sand, gravelly; about 20% hard, angular gravel particles 1/2 inch maximum size; rounded and sub-angular sand grains coarse to fine; about 15% non-plastic fines with low dry strength; Well compacted and moist in places; alluvial sand; (SM).
>
> For Fine-grained soils: Give typical name, indicate degree and character of plasticity, amount and maximum size of coarse grains, color in wet condition, odor if any, local or geologic name, and other pertinent descriptive information; and symbol in parentheses. For undisturbed soils add information on structure, stratification, consistency in undisturbed and remolded states, moisture and drainage conditions.
>
> Example: Clayey silt, brown, slightly plastic, small percentage of fine sand, numerous vertical root holes, firm and dry in place, loess, (ML).

Laboratory Classification

The same descriptive information that is required for field classification is also needed for laboratory classification. The field classification is refined by employing laboratory equipment to perform simple and routine tests to determine gradation and the Atterberg Limits. The gradation of soil material is determined by sieve analysis, and a grain-size curve is usually plotted as per cent finer (or passing) by weight against a log scale of grain size in millimeters while the Atterberg Limits are determined by measuring the amount of plasticity of the soil fraction finer than the No. 40 sieve.

Atterberg Limits--

The Atterberg Limits are a useful and qualitative measure of the mechanical properties of a particular soil. They are based on the fact that a fine-textured soil material can exist in any of four states depending on water content. The different states are separated by 'limits' termed: (1) shrinkage limit; (2) plastic limit; and (3) liquid limit. As the amount of liquid is increased, the consistency of the soil material changes. Unlike solid or fluid systems, soil material also behaves as a particulate system in the plastic state. These limits are by no means absolute and are sensitive to several environmental and operative factors.

Shrinkage Limits-- The shrinkage limit defines the moisture content of a soil material when it passes from the solid to the semisolid state. ASTM D-427-61 is the standard method for determining the shrinkage limit. Basically, the water content is determined just after enough water has been added to fill all the voids of a dry pot of soil in a special apparatus.

Plasticity-- Plasticity is the ability of a soil material to change shape continuously under the influence of an applied stress, and to retain the new shape once the stress is removed. In contrast, elastic material rebounds and fluid material has no shape. It is mainly the clay-size particles that exhibit plastic behavior.

For a soil material to be plastic, there must be sufficient water content so that the particles are able to move or slide past one another to take up new positions, and then retain these new positions. The cohesion between particles must be sufficiently low to allow this movement and yet sufficiently high to allow the particles to maintain the new position (Yong and Warkentin, 1975).

Plastic Limit-- The plastic limit is the moisture content where a soil material changes from the semisolid to the plastic state. Generally, the plastic limit is the water content at which a 3.2 mm diameter thread of soil material begins to crack and crumble under continued rolling by hand. For complete procedures, see ASTM D-424-59.

Liquid Limit and Plasticity Index-- The liquid limit is the water content when a soil material changes from the plastic to the liquid state. The test is accomplished in a standard liquid limit device. The liquid limit is the water content at which a groove cut is closed in the device after 25 taps. For standard methods, refer to ASTM D-423-66.

The plasticity index for a soil material is calculated by subtracting the plastic limit from the liquid limit. Both the plasticity index and the liquid limit values are used to determine the Unified Soil Classification of fine-grained soils.

Activity-- Since both the type and amount of clay influence the Atterberg Limits of a particular soil, the term Activity has been developed (Skempton, 1953) to mean the ratio of the plasticity index to the clay fraction (percentage by weight of particles finer than 0.002 mm). For many clays, a graph of plasticity index versus clay content for several samples will give a straight line passing through the origin. The slope of such a line yields the activity of that soil.

The laboratory criteria for classifying soils are presented in Table 2-4 and listed below in narrative form: (1) Determine if the soil is coarse-grained, fine-grained, or highly organic by determining the amount of soil passing the No. 200 sieve; (2) If coarse-grained: (a) Perform a sieve analysis and plot gradation curve on a grain-size chart. Also determine percentage passing the No. 4 sieve and classify as gravel or sand; (b) Determine amount of material passing the No. 200 sieve and if the fine fraction does not interfere with the soils' free-draining properties, examine shape of the grain-size curve, and if well-graded, classify as GW or SW; if poorly graded, as GP or SP; (c) If between 5 percent and 12 percent of the material passes the No. 200 sieve, it is a borderline case, and the classification should have a double symbol approximate to grading and plasticity characteristics (GW-GM, SW-SM, etc.); (d) If more than 12 percent passes the No. 200 sieve, perform the liquid limit and plastic limit tests on the minus No. 40 sieve fraction. Use the plasticity chart to determine the correct classification; (3) If fine-grained: (a) perform liquid limit and plastic limit tests on minus No. 40 sieve material. If the liquid limit is less than 50, classify as "L" and if the liquid limit is greater than 50, classify as "H"; (b) For "L": if limits plot below "A" line and the hatched zone on the plasticity chart, determine by color, odor, or the change in the liquid limit and plastic limit caused by oven-drying the soil, whether it is organic (OL) or inorganic (ML). If the limits plot in the hatched zone, classify as ML-CL. If the limits plot above the "A" line and the hatched zone on the plasticity chart, classify as CL; (c) For "H": if the limits plot below the "A" line on the plasticity chart, determine whether organic (OH) or inorganic (MH). If the limits plot above the "A" line, classify as CH.

SECTION 3

SOIL WATER

The variable amount of water contained in a unit mass or volume of soil and the energy state of that water affect many physical and chemical soil properties such as: consistency, plasticity, compactibility, shrinkage or swelling, soil creep, erosion, and hydraulic conductivity.

3.1 THE SOLID FRAMEWORK

The solid phase of the soil water system consists of mineral particles of many sizes and shapes, arranged in a multitude of ways, with some organic materials intermingled throughout, and comprises about 60% of the volume of a soil. It is the size, shape, and arrangement of these mineral particles that determine the size, shape and distribution of pores. Such pores, in turn, influence the amount of fluids contained in the pores and the rate of transfer of the fluids through the system. Another complicating factor is that the fluids, especially water, can alter the pore geometry by dislodging and moving solid particles within the system and by causing swelling (or shrinking) of some mineral particles. Freezing and thawing of the soil and root action can also alter the pore geometry.

3.2 THE POROUS NETWORK

Every soil material is composed of solid particles with the remaining spaces called voids or pores which make up the porous network through which water in the soil moves. Although the shape of the spaces resulting from the regular packing of the spheres is known, pores in many soil materials demonstrate that factors in addition to simple packing have influenced their shape, size, and arrangement. In many soil materials a significant proportion of the pore spaces consists of pores of comparable size interconnected by very much smaller pores, while other soils may have systems of interconnected planar voids which meet at relatively sharp angles.

Pores found in natural soils range in dimensions from those that would accommodate burrowing animals to those that would hold no more than a few layers of water molecules. If one were to dislodge a large soil fragment from the exposed face of a soil profile, the resultant soil aggregate would contain numerous pores that usually would be smaller than a few millimeters in diameter. In some cases, the line of weakness which allowed the fragment to be dislodged would, in itself, be a pore of large planar extent.

Porosity (n) and Void Ratio (e)

The porosity is an index of the relative pore volume in a given soil sample. Its value generally lies in the range of 0.3-0.6 (usually expressed as a percentage, 30-60%). While coarse-textured soils tend to be less porous than fine-textured soils, they contain individual pores of larger mean diameter. The porosity of fine-textured soils is highly variable as the soil alternatively swells, shrinks, aggregates, disperses, compacts, and cracks. A laboratory method for determining porosity can be found in Vomocil (1965).

$$\text{Porosity} = \frac{\text{Volume of Pores}}{\text{Total Volume of Soil Mass}}$$

The void ratio is also an index of the fractional volume of soil pores, but it relates the pore volume to the volume of pore solids rather than to the total volume of the soil mass. Generally the void ratio varies between 0.3-2.0 and is expressed as a decimal value.

$$\text{Void Ratio} = \frac{\text{Volume of Voids}}{\text{Volume of Soil Particles}}$$

The difference between these two indices is that a change in pore volume will change only the numerator in the Void Ratio equation, whereas a change of pore volume in terms of the Porosity equation will change both the numerator as well as the denominator. Void ratio is the generally preferred index in engineering uses of the soil, whereas porosity is the more frequently used index in the agricultural sciences. The relationships between porosity (n) and void ratio (e) are shown below.

$$n = e/(1 + e) \quad \text{and} \quad e = n/(1 - n)$$

Pore Size Distribution

While both porosity (n) and void ratio (e) are indices determining the total amount of pore space in a soil, they do not provide any information regarding the width, shape, continuity or tortuosity of the pores. For this reason, the pore size distribution is a common parameter used to describe pore geometry.

Morphometric techniques are available for measuring pore-size distributions and shapes of pores in thin sections. A detailed description of these methods can be found in Brewer (1976), Jongerius (1974), and Ismail (1975) which explain the general principles of quantitative morphological measurements of soil pores using conventional point count techniques or modern electro-optical image analysis.

Mechanical determinations of pore-size distribution are possible in two ways: (1) by forced intrusion of a non-wetting fluid such as mercury, and (2) by use of a pressure plate apparatus. The mercury intrusion method has been applied to clays (Diamond, 1970 and Ahmed, Lovell, and Diamond, 1974). The basis of the method is that a nonwetting fluid will not enter pores without application of pressure. The volume of mercury intruded into an evacuated dry sample of the order of 1 g. in size using successively higher pressures is measured. The total volume of mercury introduced at each pressure gives the total volume of pores with an equivalent diameter larger than that corresponding to that pressure. The pressure plate method is based on the incremental increase of suction on a soil required to remove water from progressively smaller pores. Brewer (1976) has stated that the mercury intrusion method is more suitable on clay soils than the pressure plate technique.

3.3 SOIL WETNESS OR MOISTURE CONTENT

The relative water content of the soil can be expressed as a percentage by weight (w), or percentage by volume (θ):

$$w = \frac{\text{Mass of Water}}{\text{Oven Dry Weight of Soil}} \times 100$$

$$\theta = \frac{\text{Volume of Water}}{\text{Volume of Soil Sample}} \times 100$$

These methods, which involve sampling, transporting to the laboratory, and repeated weighings, entail some inherent errors (Bouma, 1977). Also, they are laborious and time consuming since a period of at least 24 hours is usually allowed for complete drying. The laboratory method is also somewhat arbitrary since some clays may still contain appreciable amounts of absorbed water when oven-dried at 105 degrees Centigrade. Additionally, the sampling procedure for the laboratory method is destructive and may disturb an experimental plot sufficiently to distort the results. For these reasons, many workers prefer in situ methods which permit frequent or continuous measurement of the same points, and, once the equipment is installed and calibrated, with much less time and labor. Such methods include electrical resistance of porus blocks, neutron scattering, and gamma-ray absorption. Descriptions of these in situ methods can be found in Hillel (1980).

3.4 SOIL MOISTURE POTENTIAL

The study and occurence of movement of water in the soil relies completely on the basic concepts of the soil moisture potential, which are essentially based on thermodynamic principles. Water moves from points where it has a higher potential energy status to points where it has a lower potential status. The total potential or energy per unit quanity of water (ψ_t) is defined as the mechanical work required to transfer a unit quantity (e.g., unit mass weight or volume) of water from a standard reference state ($\psi=0$) to one where the potential has the defined value. The total potential (ψ_t) of water is composed of several components, which will be elaborated separately. For a more detailed analysis than is presented here, the reader can consult: Rose (1966), Hillel (1971), Childs (1969), Baver et al. (1972), ISSS (1976), or Hillel (1980).

Pressure Potential (ψ_p or h)

Soil wetness refers solely to the total amount of liquid in a soil sample. Additionally, it is important to ascertain the distribution of water in the soil at different moisture contents and to understand the natural laws that govern it. As the moisture content of the soil sample decreases, water leaves the larger soil pores but remains in the finer ones because the smallest pores can "pull" the strongest. This can be explained by considering the basic phenomena of liquid surface tension and capillarity.

Surface tension occurs typically at the interface of a liquid and a gas. Molecules in the liquid attract each other from all sides. In the surface areas the molecules are attracted into the denser liquid phase by a force greater than the force attracting them into the gaseous phase. The resulting force draws the surface molecules downward, which results in a tendency for the liquid surface to contract.

Capillarity refers to the phenomenon of the rise of water into a capillary tube inserted in water, due to its surface tension. The finer the tube, the higher the capillary rise and the greater the negative pressure below the water meniscus in the tube.

Gravitational Potential (ψ_g)

Each body on the earth's surface is attracted toward the center of the earth by a gravitational force equal to its weight. To raise the body against this attraction, work must be done, and this work is stored in the raised body as gravitational potential energy (Z) which is determined at each point by the elevation of the point relative to some arbitrary reference level. Therefore:

$$\psi_g = mgZ$$

where ψ_g = The gravitational potential energy of a mass m of water at a height Z above a reference, and
g = acceleration of gravity.

This potential, expressed per unit weight, becomes ψ_g = Z (cm).

Other Potentials

The potential energy of a body was defined as energy present by virtue of its presence in a force field. Pressure forces and gravitational forces have been discussed so far, and they are the most important when water movement under field conditions is considered in non-saline soils. The effect of solutes on the total potential of soil water, expressed by the osmotic potential ψ_o, becomes of primary significance if the water is separated by a membrane whose permeability to water molecules differs from that to the solute. This potential is important in water movement into and through plant roots, in which there are layers of cells which exhibit different permeabilities to solvent and solute.

Some concluding remarks must be made regarding the pressure potential ψ_p. This potential characterizes the state of water in the soil (together with ψ_g and ψ_o), including the effect of the presence of an external gas pressure different from atmospheric and/or the presence of a mechanical envelope pressure (also called an overburden pressure). The pressure potential has some subcomponents (ISSS, 1976). The pneumatic potential ($\psi_p{}^2$) is due to excess gas pressure; the envelope-pressure potential (ψ_{pe}) or overburden potential, is due to matrix pressures, for example,in swelling soils. Using the two subcomponents, which often can not be measured specifically, two additional potentials are defined. These are: (i) the matric potential, which is a pressure potential with a given envelope potential but with the pneumatic potential = 0; and (ii) the wetness potential, which is a pressure potential where the envelope and pneumatic potential both equal zero (ISSS, 1976).

Hydraulic head (H)

The hydraulic head is the sum of the gravitational and pressure potentials:

$$H = Z + h$$

where H = hydraulic head
Z = the height of the point under consideration above a reference level, and
h = the height of a vertical water column which would exert a pressure at its base numerically equal to the soil-water pressure (negative in unsaturated soil, zero or positive in saturated soil).

The hydraulic head is a very convenient concept for describing water movement and is often used in the literature.

3.5 MOISTURE RETENTION CURVE, MOISTURE CHARACTERISTIC, OR THE RETENTIVITY CURVE

In a saturated soil at equilibrium with free water at the same elevation, the actual pressure is atmospheric and the soil liquid pressure is zero. If a slight negative pressure is applied to this water, no outflow may occur until, as the pressure is further decreased, a certain critical value is exceeded at which the largest pore begins to empty. The value of this critical pressure is usually very small in coarse-textured or well-aggregated soils where large pores will immediately lose their water when only a very small negative pressure is applied. As the pressure is decreased (suction increased), more water is drawn out of the soil and more of the relatively large pores, which cannot exercise an adequate capillary force to retain their water against the pressure applied, will empty. A gradual decrease in pressure will result in the emptying of progressively smaller pores until, at high negative pressures, only the very narrow pores retain water. A decreasing pressure is thus associated with decreasing soil wetness. The rate of decrease is characteristic for any particular porous medium because it is a function of the pore-size distribution. The curve which shows the relationship between the negative pressure and the water content is a very important soil physical characteristic and is known as the soil moisture retention curve, the soil moisture characteristic, or the liquid retentivity curve (ISSS, 1976). Retention curves relating water content to pressure potential for four USDA textural classes is shown in Figure 3.1. Also, the slope of the retentivity curve ($d\theta/dh$) is called the water capacity $[C(\theta)]$ which is the rate of change of water content (θ) with the soil matric potential (ψ_m) expressed per unit volume.

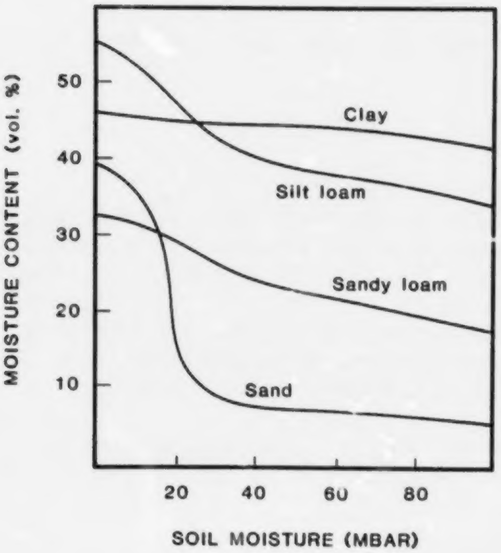


Figure 3.1 Soil moisture retention curves for four different soil materials (SSWMP, 1978).

3.6 HYSTERESIS

Unfortunately, the moisture content is not a single function of the pressure potential. The moisture content corresponding with a certain pressure is higher when it has been reached by desorption (drying) of an initially wetter sample than when reached by wetting (adsorption) of an initially drier sample. Said another way, it is harder to get water out of the soil once it is in, than to get it back in once it is out. The phenomenon of hysteresis can be illustrated by considering a schematic void partly filled with water (Figure 3.2). The water-filled idealized void (Figure 3.2a) will drain in the course of a desorption process if the negative pressure exceeds the relatively large capillary force corresponding with the smallest pore diameter (2r) in the system. The idealized air-filled void (Figure 3.2b) will fill with water in the course of an adsorption process as soon as the relatively small capillary force, corresponding with the largest pore diameter (2R), is sufficiently strong to pull the water in. This comparison shows that the water content of the soil at a given moisture tension will be greater following desorption (drying) than following adsorption (wetting) (Figure 3.3).

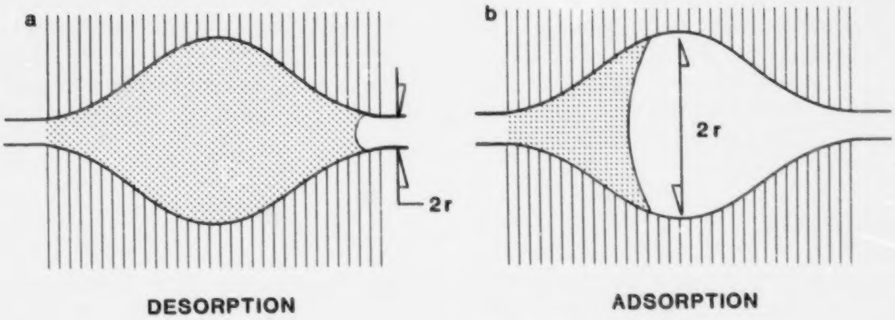


Figure 3.2 Cross-section through an idealized void illustrating the hysteresis phenomenon (SSWMP, 1978).

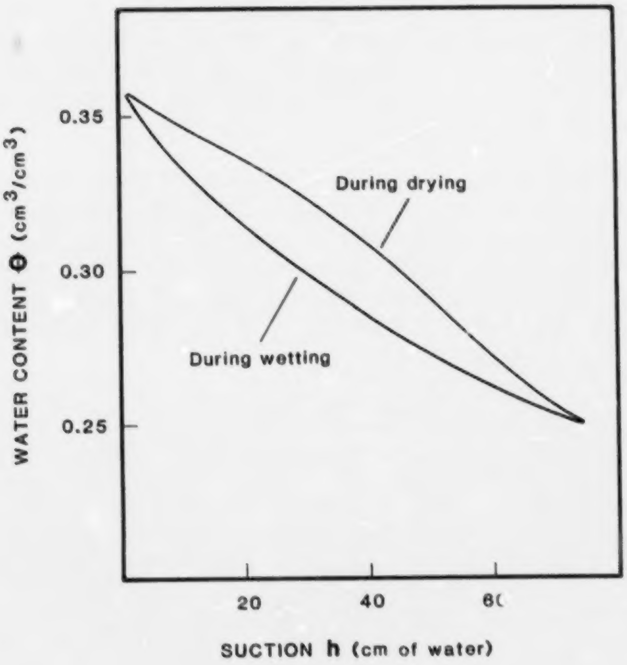


Figure 3.3 The relations between water content (θ) and suction (h) (Tzimas, 1979).

Since the moisture retention curves are usually determined by a desorption process starting with a saturated soil, values thus obtained may not apply to water contents and moisture potentials occurring in the field when an initially dry soil is wetting up. However, a physically correct characterization of the extent of hysteresis on a given soil is a very elaborate procedure (Gillham et al., 1976).

3.7 ANISOTROPY

Anisotropy is the term used to describe the fact that soil properties can vary with depth as well as horizontally. It is basically the result of weathering of rocks or sedimentary bodies and of the reorganization, translocation, and concentration of the more mobile constituents due to the effects of the environment (Brewer, 1976). Unfortunately, anisotropy in soils is the rule rather than the the exception, which has severe ramifications with regard to soil testing methods for hydraulic conductivity and interpretations of results.

Soils are stratified formations consisting of distinct layers (horizons) which have differences in particle size distributions, structure, boundary conditions, and other properties which effect the hydraulic properties of each horizon on a macroscopic level (soil series) as well as on the microscopic level (soil fabric). Such differences will influence both vertical and lateral hydraulic conductivity.

At the soil series level, anisotropy is manifested in two ways: 1) horizons vary in depth as well as thickness and can exhibit anomalies such as vertical sand seams or clay lenses, and 2) boundary conditions between soil horizons can sometimes influence overall water movement more than the properties of the mass of the horizon itself. This is shown graphically in Fiqure 3.4.

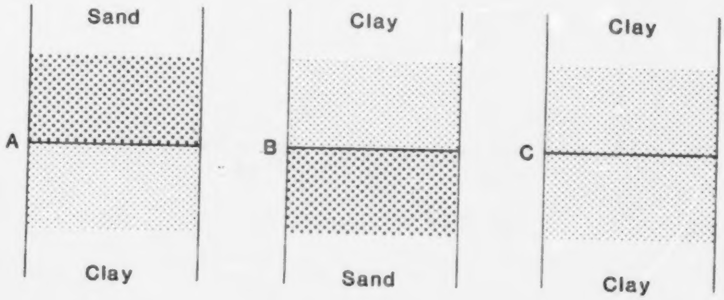


Figure 3.4 Influence of underlying layer on hydraulic conductivity

In Case A, water added to the sand will flow quickly through the sand into the clay, while in Case B, no water will enter the sand layer until the clay layer is nearly saturated because the water is held by the finer pores in the clay horizon. Therefore, the clay horizon in Case B might hold up to two or three times as much water as the upper clay horizon in Case C.

3.8 WATER MOVEMENT IN SOILS

Water movement in soils can be divided into types of flow systems for general considerations: (1) saturated flow where all pores are filled with water, and (2) unsaturated flow where both air and water are present in the pores.

The basic equation for describing water flow through porous materials, whether saturated or unsaturated flow, is expressed by Darcy's Law:

$$J = K \; \Delta H$$

where J = flux, volume of liquid moving through a unit cross-sectional area of soil per unit of time
K = hydraulic conductivity
ΔH = hydraulic gradient

The hydraulic conductivity, K, is not constant; rather, it varies with changes in the water content as well as with changes in pressure head. Therefore, K can be expressed as either a function of water content, $K(\theta)$, or as a function of pressure head, $K(h)$. For determination of either function, the soil moisture characteristic (retentivity curve) usually must be known, also. Figure 3.5 demonstrates two different cases: A) water capacity functions for four soils with respective hydraulic conductivity curves expressed as a function of pressure head, and B) water capacity function for one soil and its hydraulic conductivity relation expressed as a function of water content.

The hydraulic conductivity is one of the most variable soil properties of importance to waste disposal concerns as it exhibits a great range of values (up to fourteen orders of magnitude) from coarse to very fine-grained soils.

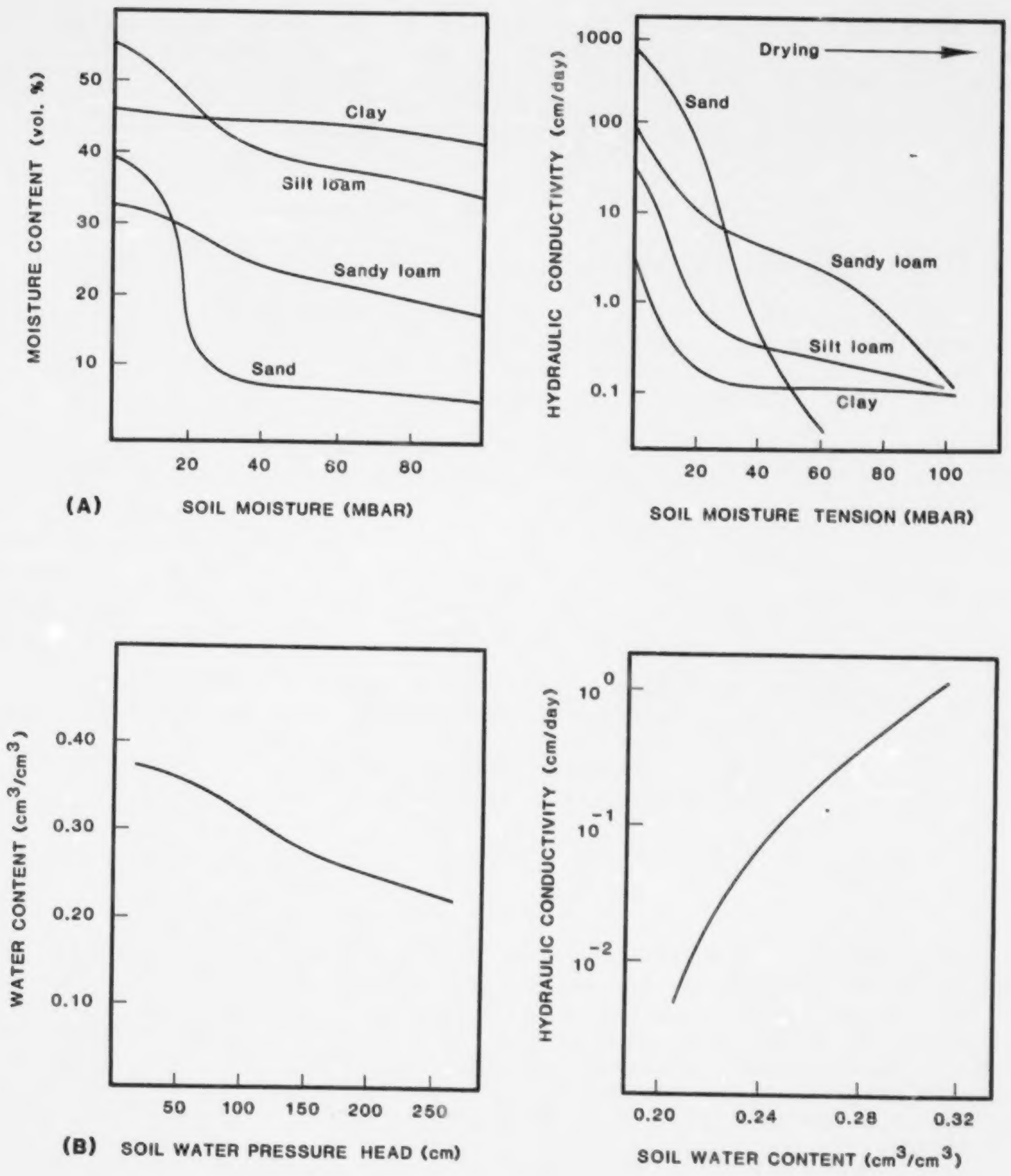


Figure 3.5 Water retention curves and hydraulic conductivity (A) water retention curves and hydraulic conductivity as a function of pressure head (SSWMP, 1978), and (B) water retention curve and hydraulic conductivity as a function of water content (Flocker et al., 1968).

Saturated Flow

The determination of saturated hydraulic conductivity is physically easier and conceptionally simpler than the determination of unsaturated hydraulic conductivity because the purpose is to find the hydraulic conductivity at one point, ($h = 0$, $\theta =$ constant), rather than over the range of pressure heads or range of water contents necessary for unsaturated flow, and because it is assumed that the soil pores are constantly and completely filled with water. Therefore, in the determination of saturated flow, the hydraulic conductivity is considered to be constant.

However, in a given soil, K may not remain the same due to such processes as particle arrangement within the soil matrix over time. Also, depending on the mode of wetting, saturated soils rarely have all soil pores completely filled with water. It is not unusual to expect 2-12% air remaining in the soil pores (Yong & Warkentin, 1975). This implies that attention should be placed on the mode of saturation because if K is determined for the situation with entrapped air, it is basically an unsaturated flow situation, and unsaturated flow will always be less than saturated flow. (See Figure 3.5(A), which demonstrates that saturated K equals the intercept on the abscissa and that hydraulic conductivity decreases (sometimes sharply) as the pressure head decreases from saturation, $h = 0$.)

For saturated flow testing methods, the basic approach is to measure flow and total pressure or hydraulic pressure gradient and calculate the hydraulic conductivity from Darcy's equation.

Unsaturated Flow

The situation for unsaturated hydraulic conductivity is much more complex than for saturated flow because the purpose is to determine a complete hydraulic conductivity function over a range of water contents or pressure heads rather than just one point as for saturated flow.

For saturated flow testing methods, there is quite a variety of techniques that measure different parts of the water capacity, diffusivity, or hydraulic conductivity functions during steady or transient (unsteady) state conditions. Such methods range from transient state field methods that measure flow, pressure head, and water content to steady state laboratory methods that measure flow and pressure head or water content with other inferred to transient state field methods that calculate hydraulic conductivity from water content only.

The soil water diffusivity is defined as:

$$D(\theta) = K(\theta)\frac{dh}{d\theta} = \frac{K(\theta)}{C(\theta)}$$

where $D(\theta)$ = the soil water diffusivity function
$K(\theta)$ = the hydraulic conductivity function
$C(\theta)$ = the water capacity function
$\frac{dh}{d\theta}$ = reciprocal of slope of $C(\theta)$ function at a particular water content

Although soil water diffusivity is somewhat difficult to visualize physically, it is mathematically simple, being the product of the hydraulic conductivity at a given water content and the reciprocal of the slope of the retentivity curve at the same water content. Likewise, if hydraulic conductivity is to be determined, the equation can be rewritten as:

$$K(\theta) = D(\theta)\frac{d\theta}{dh}$$

where $K(\theta)$ = hydraulic conductivity function
$D(\theta)$ = soil water diffusivity function, and
$\frac{d\theta}{dh}$ = slope of water capacity curve/soil water characteristic at a particular water content.

The situation for hydraulic conductivity determination is graphically presented in Figure 3.6 (A), (B), and (C). Given the diffusivity function (A) and the retentivity curve (B), the hydraulic conductivity at a particular water content, θ_1, is equal to the diffusivity at θ_1 times the slope of the retentivity at θ_1, $^{d\theta}/dh\ 1$. Doing this same procedure over the range of water contents will determine (C) the hydraulic conductivity function.

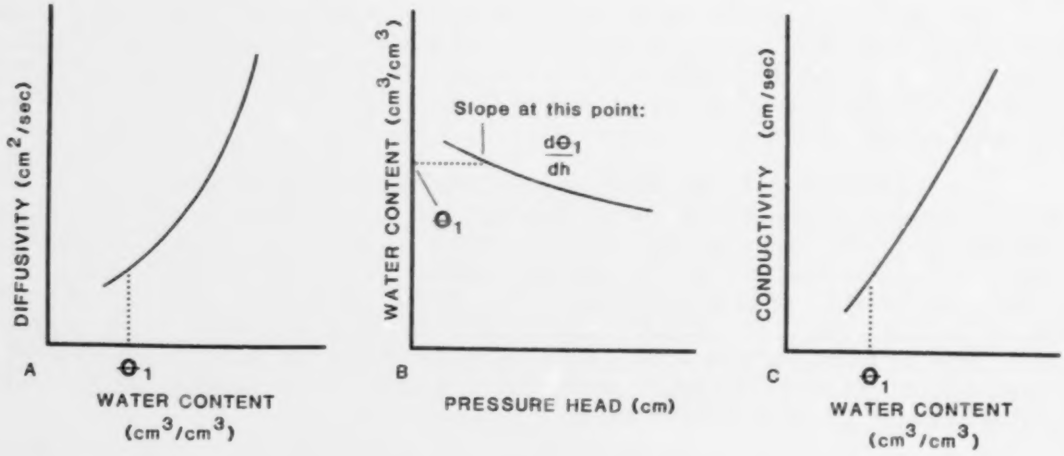


Figure 3.6 Graphic representation of hydraulic conductivity determinations from diffusivity measurements.

3.9 HYDRAULIC CONDUCTIVITY AND SOIL PORE GEOMETRY

Since hydraulic conductivity is a characteristic physical property of a porous media, it would seem reasonable to assume that it relates to specific measurable properties of the soil pore geometry, e. g., porosity, pore-size distribution, internal surface area, etc. However, the many attempts to develop a functional relation of universal applicability for the range of soils and soil materials, has been generally unsuccessful.

The simplest approach is to seek a correlation between hydraulic conductivity and total porosity. However, it can be concluded that such an approach is generally futile (except for comparison of otherwise identical media) owing to the strong dependence of flow rate upon width, continuity, shape, and tortuosity of the conducting pores. This is the reason why coarse-textured soils (with less total porosity and fewer individual pores, but larger and more uniformly sized pores) will have greater saturated hydraulic conductivity than fine-textured soils (which have greater total porosity, but smaller, more irregularly-sized, tortuous pores).

Numerous theoretical models have been introduced to represent porous media by a set of relationships that are amenable to mathematical treatment. Scheidegger (1974) gave a comprehensive review of such models, including the straight capillaric, parallel, serial, and branching models and concluded that the preferred model of a porous medium should be based upon statistical models.

One of the most widely accepted theories on the relation of saturated hydraulic conductivity to the geometric properties of porous media is the Kozeny-Carman theory which is based on the concept of hydraulic radius. The measure of hydraulic radius is the ratio of the volume to the surface of the pore space, or the average ratio of the cross-sectional area of the pores to their circumferences. The Kozeny-Carman equation is shown below:

$$K = \frac{1}{k_o T^2 S_o^2} \left(\frac{n^3}{(1-n)^2} \right)$$

where K = saturated hydraulic conductivity
k = pore shape factor (approximately equal to 2.5)
T = tortuosity factor (approximately equal to square root of 2)
S = specific surface area per unit volume of particles
n = porosity

Although the Kozeny-Carman equation works well for the description of saturated hydraulic conductivity in uniformly graded sands and some silts, serious discrepancies are found in clays (Michaels and Lin, 1954, Lambe, 1955, and Olsen, 1962). The failure ot this theory stems from the original assumptions which are: (1) no pores are sealed off, (2) pores are distributed at random, (3) pores are reasonably uniform in size, (4) porosity not too high, (5) diffusion phenomena are absent, and (6) fluid motion occurs like motion through a batch of capillaries (Scheidegger, 1974). Soil systems which can satisfy every assumption are rare to nonexistent with the exception of uniformily graded sands upon which the Kozeny-Carman equation was founded.

A more promising approach to the prediction of hydraulic conductivity from physical properties of the porous medium is to seek a connection between hydraulic conductivity and pore-size distribution. However, since it is difficult to determine the pore-size distribution per se either physically or morphologically, it is often preferred to work with parameters based on the suction or capillary pressure versus sorption or desorption. Since flow through an irregular pore is limited by the narrow bottlenecks along the flow paths, it is necessary to consider or estimate the number and size of such bottlenecks and the interconnections of pores of different widths. Initial work along these lines has been published by Childs and Collis-George (1950), Marshall (1958), and Millington and Quirk (1960, 1961, 1964) and has been expanded upon with the use of matching factors by numerous authors including Kunze (1968), Green and Corey (1971), Roulier et al. (1972), Neilsen et al. (1973), Carvallo et al. (1976), Simmons et al. (1979), Libardi et al. (1980), and Dane (1980). However, the results of these procedures (while more generally applicable than those based on earlier models) still appear to be valid for only coarse-textured materials with hydraulic conductivities greater than 0.0001 cm/sec.

3.10 HYDRAULIC CONDUCTIVITY AND ANISOTROPY

As discussed earlier in this section, anisotropy in soils is defined as the condition where soil properties are different in different directions and is generally thought to be due to the structure of the soil, which may be laminar, or platy, or columnar, etc., thus exhibiting a pattern of micropores or macropores with a distinctly directional bias.

Anisotropic soil conditions will affect flow direction as there are both horizontal and vertical components to the hydraulic conductivity function. Table 3-1 shows ratios ot horizontal hydraulic conductivity to vertical hydraulic conductivity for fine-textured soils as found in the literature. Generally, for varved or stratified clays, the ratio may exceed ten whereas for less stratified soils, the ratio is likely to be closer to one.

TABLE 3-1 DATA ON THE RATIO OF HORIZONTAL TO VERTICAL HYDRAULIC CONDUCTIVITY OF FINE-TEXTURED SOILS

Reference	Horizontal K/Vertical K
Tsien (1955)	1.2 - 1.7
Mitchell (1956)	1.0 - 7.0
Basett and Brodie (1961)	1.5
Olsen (1962)	0.9 - 4.0
Lumb and Holt (1968)	1.2
Morgenstern and Tchalanko (1967)	2.0
Casagrande and Poulos (1969)	4.0 - 40.0
Haley and Aldrich (1969)	0.7 - 3.3
Chan and Kenney (1973)	1.5 - 3.7
Kenney and Chan (1973)	1.5
Subbaraju et al. (1973)	1.05
Wu et al. (1978)	3.0 - 15.0

At the microscopic level, soil fabric will also exhibit anisotropy which can cause substantial hydraulic conductivity anisotropy. In a section on fabric and permeability, Mitchell (1976) states, "Of the properties of importance in the analysis of geotechnical problems in fine-grained soils, none is more influenced by fabric than the hydraulic conductivity."

Further, fabric may be developed in initially homogenous soils from shear or compression forces. The amount of shear or compression required for development of anisotropic fabric varies for mineral soils, and depends on such factors as soil mineralogy, composition of pore fluid, and initial fabric (Mitchell, 1976).

A practical ramification of soil fabric anisotropy is that hydraulic conductivity of a clay soil is dependent on the structure and fabric to such an extent that analysis based on properties determined from the same material, but with a different structure may be totally in error. That is, where fabric and isotropy can affect a parameter being tested (such as the hydraulic conductivity of clay soils), laboratory results often may not reproduce field results due to sampling and preparation procedures of laboratory methods which will change soil fabric.

As a result, many researchers have expressed doubts that laboratory hydraulic conductivity tests are capable of reproducing field conditions. Olson and Daniel (1981) noted that the volume of soil samples used in laboratory tests are almost always too small to contain statistically significant distributions of macrofeatures encountered in the field such as sand lenses, channels, root holes, etc. They also noted that samples taken in the field may be affected either by collection method or selection of the most uniform or intact sample. Bowles (1978) stated that "The soil in the permeability device is never in the same state as in the field - it is always disturbed to some extent." Therefore, extrapolation of laboratory results to field conditions should only be used with caution and supporting justification.

3.11 HYDRAULIC CONDUCTIVITY AND PERMEANT

The hydraulic conductivity of a certain soil is not an exclusive property of the soil alone since it depends on the attributes of the soil and the permeating fluid (permeant) together. Properties of the permeant that will affect hydraulic conductivity of a soil are viscosity and density. The terms hydraulic conductivity and permeability are often used interchangeably.

In contrast to hydraulic conductivity (permeability) the intrinsic permeability is an exclusive property of the soil and is independent of the properties of the fluid, provided that the fluid does not change the properties of the soil. The hydraulic conductivity, intrinsic permeability, and fluid properties are related as follows:

$$K = k\eta g/\rho$$

Where: K = hydraulic conductivity(permeability) ($\mathrm{cm\ sec^{-1}}$)
k = intrinsic permeability ($\mathrm{cm^{2}}$)
η = viscosity ($\mathrm{g\ cm^{-1}\ sec^{-1}}$)
g = gravitational constant ($981\ \mathrm{cm\ sec^{-2}}$)
ρ = density ($\mathrm{g\ cm^{-3}}$)

The viscosity parameter normalizes resistance due to the fluid cohesiveness, while the density parameter normalizes the effect of gravity. As the above equation indicates, hydraulic conductivity of a soil is directly proportional to density and inversely proportional to the viscosity of the permeant.

The Soil Solution

Under normal conditions, the main permeant in soil is water. However, in the situation of disposing of hazardous wastes on land, other fluids besides water will move thru the soil. Because such fluids are physically and chemically different than water, they can cause dramatic changes in soil properties which can induce changes in the hydraulic conductivity of the soil. The types of changes in soil characteristics as a result of different permeants present in the soil from waste leachate are listed below (Matrecon, 1980):

(1) The dispersion/flocculation (aggregation) properties of the soil;
(2) The alterations in the shrink/swell properties of the soil;
(3) The change of pore-size distribution characteristics;
(4) The dissolution/precipitation of chemical species which can induce changes in the proportion of soil volume available for flow; and
(5) The modification of the absorption properties of the soil.

Hazardous Waste Leachate

To determine the effect of a specific waste on the hydraulic conductivity of a soil, two different leachates must be investigated. These leachates include both the flowable constituents of the waste (primary leachate) and flowables generated from percolating water leaching through the waste (secondary leachate). Both primary and secondary leachates can be divided into a solvent phase (the predominant fluid component) and a solute phase (the components dissolved in the solvent). And while the solutes in a leachate can affect the hydraulic conductivity of a soil, usually the solvent will exert a more predominant influence.

Solvent Phase--

A high percentage of the available research on the behavior of organic fluids and hazardous waste leachates relates to systems where water is the solvent (Goring and Hamaker, 1972; Chian and DeWalle, 1977; and McDougall et al., 1979) with organic chemicals considered to be present in only trace amounts. However, in the case of hazardous waste disposal on land, while water will always be the solvent in the secondary leachate, organic compounds will usually be the solvent in primary leachate.

Organic fluids disposed in hazardous waste disposal sites will cover the full spectrum of chemical species and can be classified into four groups for evaluating the effects of such fluids on the hydraulic conductivity of a given soil. These groups are based on the physical and chemical properties that govern their interactions with clay minerals. The four groups are: (1) Organic acids; (2) Organic bases; (3) Neutral polar organics; and (4) Neutral nonpolar organics.

Organic Acids-- Organic acids are organic fluids with acidic functional groups and can be subdivided into phenolic and aliphatic acids. The proton donating properties of these acids give these fluids potential to react with and dissolve clay particles.

Brown and Anderson (1982), in conductivity studies with compacted soil specimens, reported that organic acids affected hydraulic conductivity by dissolution of clay particles followed by piping of the particle fragments through the soil. These effects resulted in sharp initial hydraulic conductivity decreases as the migrating particle fragments clogged the fluid-conducting pores. On some soils, the hydraulic conductivity later gradually increased as the acid dissolved the soil particles that had previously clogged the pores.

Organic Bases-- Organic bases are organic fluids capable of accepting a proton to become an ionized cation. Since these components are positively charged, they absorb strongly onto the negatively charged clay surfaces and can replace absorbed water which alters the clay surface chemistry and changes the behavior of a clay soil.

Organic bases have been implicated in the dissolution of clay liners in waste impoundments. Haxo (1976) found in preliminary tests that smectitic clay liners allow passage of strong bases within a short period of time. Also, Brown and Anderson (1982), reported that bases tended to cause hydraulic conductivity increases via alterations in soil structural fabric.

Neutral Polar Organics-- Neutral polar organics do not exhibit any net charge but have an asymetrical distribution of electron density resulting in an appreciable dipole movement. This property allows these compounds to compete with water for absorption sites on the negatively charged clay surfaces which, like other organic cations, will change the behavior of a clay soil. Examples are alcohols, aldehydes, alkyl halides, glycols, and ketones.

Neutral polar organic fluids tend to decrease the surface tension (and hence viscosity) of absorbed water on clay particles which results in increased hydraulic conductivity. Brown and Anderson (1982), reported that the neutral polar fluids showed continuous hydraulic conductivity increases with no apparent tendency to reach maximum values.

Neutral Nonpolar Organics-- Neutral nonpolar organics are organic fluids that have no charge and a small if any, dipole moment. This group is further subdivided into aliphatic and aromatic hydrocarbons. With low water solubilities and little polarity to compete with water for absorption sites on clay particles, these chemicals have the potential to move through soils very rapidly.

In a study of hydraulic conductivity of a clay subsoil underlying a proposed landfill site, White (1976) reported that the clay soil was highly impermeable to water while very permeable to lighter hydrocarbons. Additionally, Brown and

Anderson (1982), found neutral nonpolar fluids caused initial hydraulic conductivity increases of nearly two orders of magnitude before the soil would stabilize and the hydraulic conductivity would remain relatively constant.

3.12 HYDRAULIC CONDUCTIVITY TESTING ERRORS

Testing for hydraulic conductivity can be divided according to flow regime into saturated and unsaturated flow and each flow regime can be tested either in the laboratory or in the field according to methods described in detail in Section 6. In this discussion of testing method errors, laboratory methods will be compared to field methods.

Laboratory Tests

The main advantages of laboratory testing are economy and convenience. Laboratory tests offer financial benefits accruing from the fact that a large number of tests can be performed routinely in a well-equipped soil testing laboratory. Also, such testing can be performed by technicians, in contrast to the generally higher level of skill required for the execution and interpretation of field testing. Laboratory testing further offers protection from adverse weather conditions as they can be performed at all times, while field testing is necessarily restricted to non-rainy, unfrozen seasons, which generally means it must be performed during the summer. However, such advantages are offset by an array of disadvantages.

Limitations of Laboratory Tests--

Olson and Daniel (1981) have listed potential sources of error in laboratory tests for both saturated and unsaturated flow. These lists are presented in Table 3-2.

Of these possible sources of error, of greatest concern is the use of samples that may not be representative of field conditions. Disturbed samples that are taken back to the laboratory and repacked in the various types of apparati will not have the same fabric, structure, or pore configuration as they did in their undisturbed state. Additionally, the use of small samples compounds the disturbed soils problems by omitting macroscopic variations occurring at the field level such as sand lenses, fissures and joints, and root holes. Therefore, because laboratory tests are deficient with regard to both microscopic and macroscopic features of the soil in the field, extreme caution is urged with regard to laboratory results' extrapolation to the field scale level.

TABLE 3-2 SOURCES OF ERROR IN LABORATORY TESTING FOR SATURATED AND UNSATURATED FLOW (OLSEN AND DANIEL, 1979)

Saturated	Unsaturated
(1) Non-representative samples	(1) Non-representative samples
(2) Voids formed during sample preparation	(2) Smear zones
(3) Smear zones	(3) Incorrect flow direction
(4) Alteration in clay chemistry	(4) Growth of microorganisms
(5) Air in sample	(5) Chemical effects
(6) Growth of microorganisms	(6) Temperature effects
(7) Meniscii problems in capillary tubes	(7) Filter impedance
(8) Use of excessive hydraulic gradients	
(9) Temperature affects	
(10) Volume change due to stress change	
(11) Flow direction	

Comparison of Laboratory to Field Testing Results--

A comparison of corresponding laboratory and field hydraulic conductivity test results will show the field hydraulic conductivity to be considerable, but unpredictably higher than values measured in the laboratory. Olson and Daniel (1981) compared field and laboratory hydraulic conductivity values from the literature and found that the range of the ratios of field K/laboratory K have been reported from 0.3 to 46,000 with 90% of the observations in the range from 0.38 to 64 with field results usually being higher than laboratory results. They report the major causes of this effect as being (1) a tendency to run laboratory tests on more clayey samples, (2) the presence of sand seams, fissures, and other macrostructural features in the field that are not represented properly in laboratory tests, (3) the use of laboratory K values backcalculated from consolidation theory rather than directly measured values, (4) the measurement of vertical flow K in the laboratory and of horizontal K in the field, (5) the use of distilled water in the laboratory, and (6) air entrapment in laboratory samples.

Field Tests

While field tests have some sources of error similar to problems encountered in laboratory testing, field testing has some unique problems. One such difficulty arises from the fact that most experience in field soil testing has been on coarse-textured soils. Also, most of the field-scale experience of soil engineers, geohydrologists, and soil scientists has been experimental rather than standardized and has addressed problems such as ground water flow and soil - water - plant relations, and this information is not always completely applicable to the problems of hazardous waste landfills and surface impoundments.

Another problem associated with field-scale testing lies in the use of Darcy's Law in the flow analyses, in the excessive attention directed at the analysis rather than the value of K. This is an unfortunate occurrence because no other soil parameter is as likely to exhibit the wide range of values (from 10^4 cm sec^{-1} to 10^{-10} cm sec^{-1}) as does hydraulic conductivity. Important considerations for quantification of field level hydraulic conductivity are fabric and spatial variability, as elaborated below.

Fabric--

Of the parameters of significance in the analysis of environmental problems of fine-textured soils none is more influenced by fabric than the hydraulic conductivity (Mitchell, 1976). A simple example of this phenomenon is provided in a consideration of two equal volumes of soil (A and B) with exactly the same properties with the exception of one long continuous pore in soil volume A and four discontinuous pores with total equivalent pore volume equal to soil volume A in soil volume B. Hydraulic conductivity will be dramaticlly different between these two cases.

Therefore, it is of importance that the soil testing required for site evaluation actually test the soil fabric that will exist in the landfill or surface impoundment. The tested soil fabric will be of two separate types: soil fabric of the liner and soil fabric of the unsaturated zone between the liner and ground water table or bedrock.

The importance of soil fabric to considerations of the hydraulic conductivity of soil liners cannot be overstated. In a chapter of Fabric, Structure, and Property Relationships, Mitchell (1976) states that the main conclusion to be drawn from the considerations of his chapter is that the geotechnical properties of any given soil are dependent on the structure to such an extent that analyses based on properties determined from the same material but, with a different structure may be totally in error. Therefore, considerations of use of a particular soil for a liner must be based on soil testing methods that stimulate the field compactive effort to the highest degree possible.

As mentioned earlier, one considerable failing of laboratory tests is that the soil fabric of the tested sample will not be the same as the fabric of the soil in situ. Lambe and Whitman (1979) state that because hydraulic conductivity depends very much on soil fabric (both microstructural - the arrangement of individual particles, and macrostructural - such as stratification) and because of the difficulty of getting representative soil samples, field determinations of hydraulic conductivity are often required to get a good indication of the average hydraulic conductivity.

Spatial Variation (Ansiotropy)--

The soil is not a static body, but rather a dynamic set of processes always being affected by the soil-forming factors of climate, parent material, topography, vegetation, and time. Therefore, a soil body will vary in both the vertical and horizontal directions. For example, vertical variation is manifested in different hydraulic conductivities between successive soil horizons, and horizontal variation is manifested in differing thickness of soil horizons between soil profiles of the same soil series. Thus non-homogeneity (anisotropy) in soils is the rule rather than the exception, and soil testing of homogeneous or mixed samples for average conditions may be totally in error in predicting conditions that will exist in the field.

Additionally, during the site evaluation and review process, attention must be devoted to a qualification of errors involved in soil testing results. That is, some determination of whether the variation in soil testing results is a consequence of the soil's spatial variability or a variation inherent in the soil testing method itself. At this time, excepting the information included in the Precision and Accuracy subheading of each method in the Soil Testing Methods Section (Section 6), little information is available to quantify the components of variation in the results of many soil testing methods.

SECTION 4

SOIL COMPACTION

If a cohesive soil is compacted with a given type and amount of compactive effort at various water contents, a compaction curve such as the one shown in Figure 4.1 is obtained. This compaction curve shows that as the molding water content is increased, the dry density increases to a peak and then decreases. The density and moisture content at peak density are, respectively, maximum dry density and optimum moisture content for that particular type of compaction and compactive effort. For the Compaction Test shown in Figure 4.1, the maximum dry density (unit weight) is 18.7 kN/m^3 and the optimum moisture content is 11%.

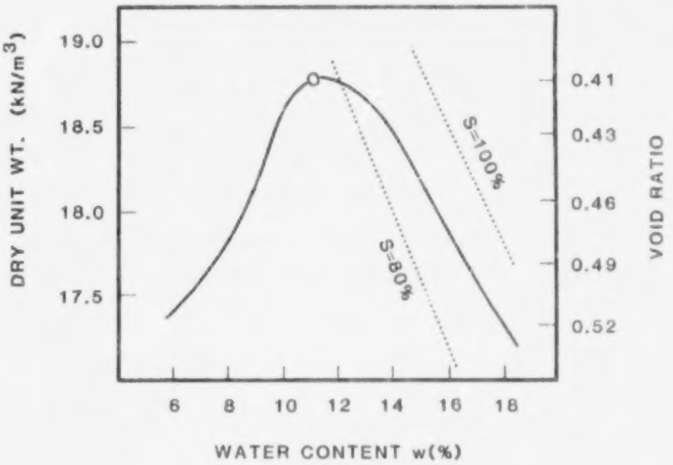
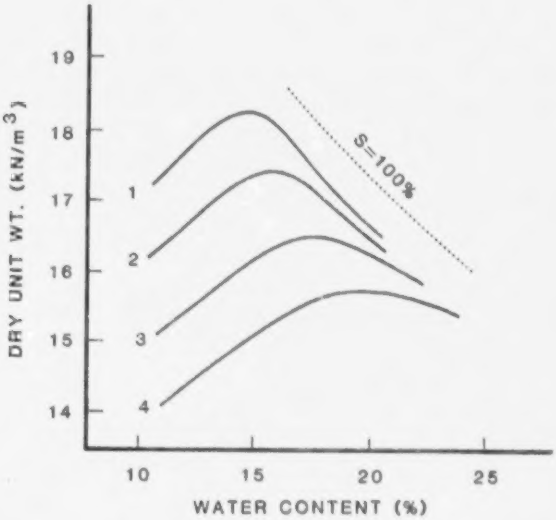


Figure 4.1 Standard compaction test (Lambe, 1951).

The computed relationship between water content and dry density at a constant degree of saturation may also be plotted on the same scale as the compaction curve. As can be seen in Figure 4.1, the degree of saturation increases with increasing water content to a value slightly above that at optimum moisture content and then tends to remain approximately constant. The moisture relationship for a specific soil depends on the amount and type of compaction, as shown by Figures 4.2 and 4.3. Figure 4.2 shows the results of four laboratory tests using impact compaction. The compaction effort was decreased from Test 1 through Test 4. Thus, for a given type of compaction, the higher the compactive effort the higher the maximum density and the lower the optimum water content. Further, as the molding water content increases, the influence of compactive effort on density tends to decrease. The points of maximum dry density and optimum water content for the various compactive efforts tend to fall along a line that parallels the lines of a constant degree of saturation.



No.	Layers	Blows per Layers	Hammer Mass	Hammer Drop	
1	5	55	4.54 kg	457 mm	(mod. AASHO)
2	5	26	5.54	457	
3	5	12	4.54	457	(std. AASHO)
4	3	25	2.50	305	

Figure 4.2 Dynamic compaction curves for a silty clay (Lambe and Whitman, 1979).

Figure 4.3 demonstrates the results of static compaction in which the compacting stress is decreased going from Test 1 toward Test 4. As shown in this figure, the higher the compactive stress, the higher the maximum density and the lower the optimum water content.

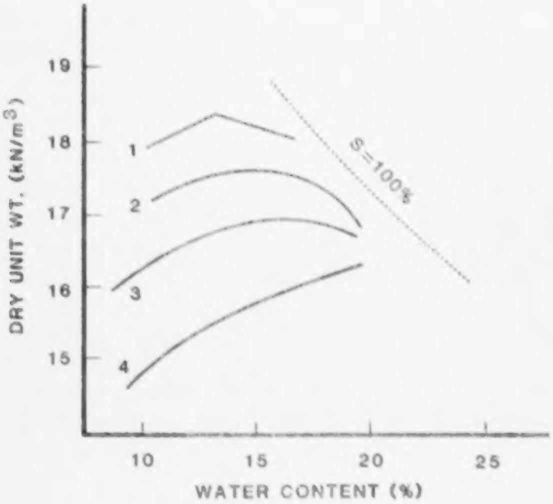


Figure 4.3 Static compaction for a silty clay (1) 13.8 MN/m^2 static load. (2) 6.9 MN/m^2 static load. (3) 3.45 MN/m^2 static load. (4) 1.38 MN/m^2 static load. Note: Compaction on top of soil sample. (Lambe and Whitman, 1979).

4.1 COMPACTION TESTS

There are many kinds of laboratory compaction tests for moisture density relations, each selected for some similarity to some type of field compaction. The oldest and most common type is frequently called a impact compaction test and is performed by placing some soil in a mold and dropping a hammer on it a specified number of times with a tamper at specified stress. In the static compaction test the soil is subjected to a static stress of a given magnitude. Details of some particular procedures can be found in ASTM D 698-78, D 1557-78, and D 1561-76.

Alternatively, field methods can be utilized to measure in situ density of soils compacted by smooth-wheel rollers, rubber-tired rollers, sheeps-foot rollers, or vibratory equipment. Two of the more reliable procedures are the sand cone method (ASTM D 1556-64) and nuclear probe methods (ASTM 2922-78). Nuclear methods have several advantages, among which are minimum disturbance of the soil, short time required for sampling, accessibility to subsoil measurements with minimum excavation, and the possibility of continuous or repeated measurements at the same point.

4.2 COMPACTION AND HYDRAULIC CONDUCTIVITY

Hydraulic conductivity of a compacted soil layer is influenced by soil properties such as structure, fabric, and porosity.

Structure

Test data which show the influence of structure on hydraulic conductivity are presented in Figure 4.4 and 4.5. Figure 4.4 shows that physically mixing or blending of a soil can have a major effect on hydraulic conductivity. Figure 4.5 shows the large influence on hydraulic conductivity obtained by mixing in 0.1% (based on dry soil weight) of a polyphosphate dispersant. The dispersant, increasing the repulsion between fine particles, permits them to move to positions of greater hydraulic stability, resulting in a reduction in hydraulic conductivity.

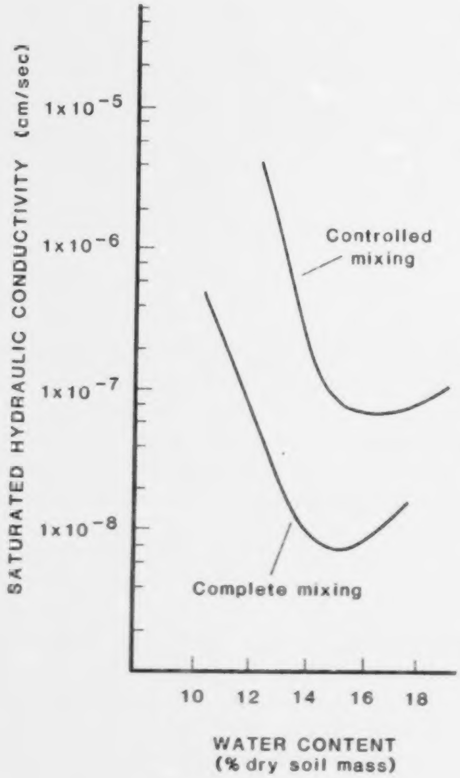


Figure 4.4 Effect of mixing on hydraulic conductivity - Jamaica clay (Lambe, 1955).

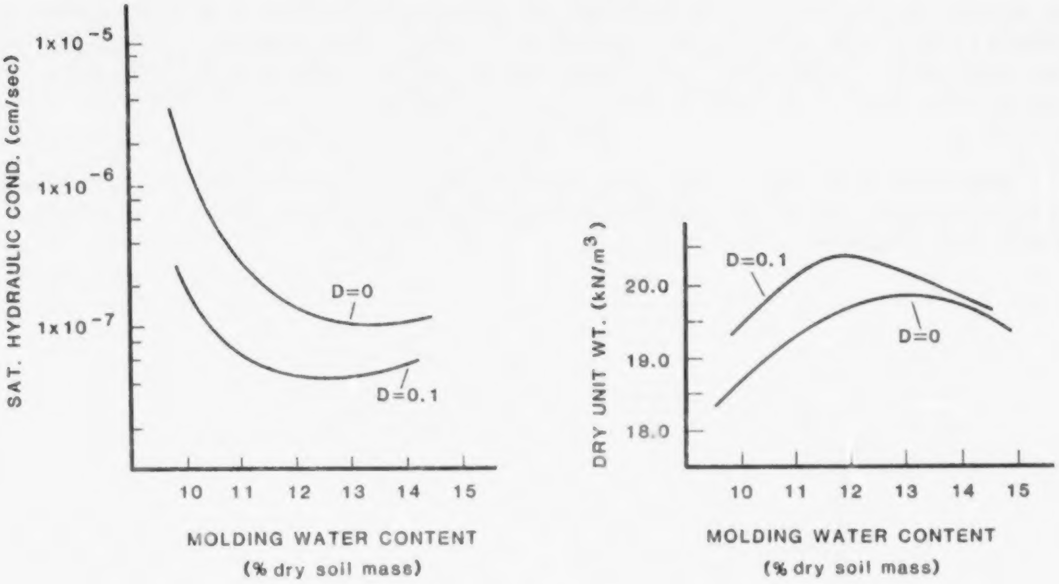


Figure 4.5 Effect of dispersion on hydraulic conductivity (Lambe, 1955)

Fabric

The fabric component of structure is one of the most important soil characteristics influencing hydraulic conductivity, especially for fine-textured soils. To suggest how large the effect of fabric on hydraulic conductivity can be, Table 4-1 gives test results obtained on a compacted clay.

TABLE 4-1 EFFECT OF FABRIC ON HYDRAULIC CONDUCTIVITY (Lambe and Whitman, 1979)

Soil	Dry Unit Weight of Mold Ratio	Degree of Saturation	Hydraulic Conductivity (cm/sec)
Jamaica	18.07 kN/m^3	Approximately	4×10^6
clay	18.22 kN/m^3	same	7×10^8
Viginia	1.3	100%	1×10^3
sandy clay	1.3	100%	2.7×10^4

The first comparison, between a sample compacted dry of optimum and one wet of optimum, shows two samples of essentially the same void ratio and degree of saturation having a hydraulic conductivity ratio of approximately 60. The second comparison, also between samples at the same void ratio and degree of saturation shows a hydraulic conductivity ratio of greater than 3.

Another example of the profound influence of compaction water content on the hydraulic conductivity of a silty clay is shown in Figure 4.6.

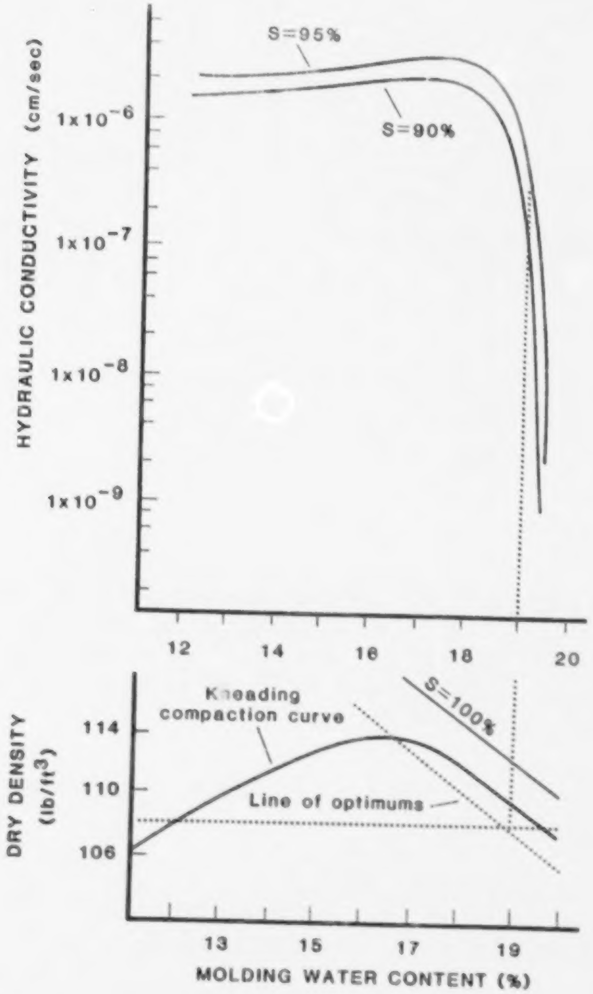


Figure 4.6 Hydraulic conductivity as a function of molding water content for samples of silty clay prepared to constant density by kneading compaction (Mitchell, 1976).

This is typical for the variation of hydraulic conductivity with water content in compacted fine-textured soils. For the example shown, all samples were compacted to the same density. For samples compacted using the same compactive effort, curves such as those in Figure 4.7 are typical.

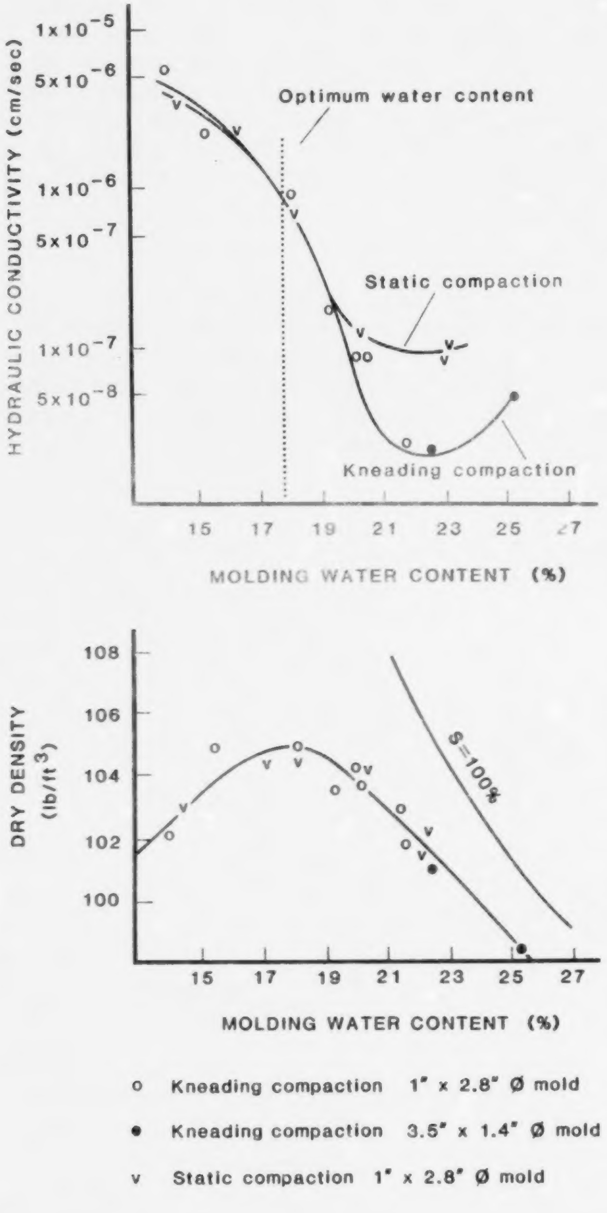


Figure 4.7 Influence of the method of compaction on the hydraulic conductivity of silty clay (Mitchell, 1976).

For compaction dry of optimum, clay particles and aggregates are flocculated, the resistance to rearrangement during compaction is high, and a fabric with comparatively large pores is formed. Since flow through one large channel will be much greater than flow through a number of channels having the same total channel area, it is readily apparent that the larger a channel for a given compactive effort, the higher the hydraulic conductivity. For higher water contents, the particle groups are weaker, and fabrics with smaller average pore-sizes are formed. Considerably lower values of hydraulic conductivity are obtained wet of optimum in the case of kneading compaction than by static compaction, because the high shear stains induced in the kneading compaction method break down flocculated fabric units.

Porosity

Data from consolidation - hydraulic conductivity tests where the hydraulic conductivity was measured at a number of porosities during compression and rebound can be compared with values predicted by the Kozeny-Carman equation. A typical result is shown in Figure 4.8 for illite.

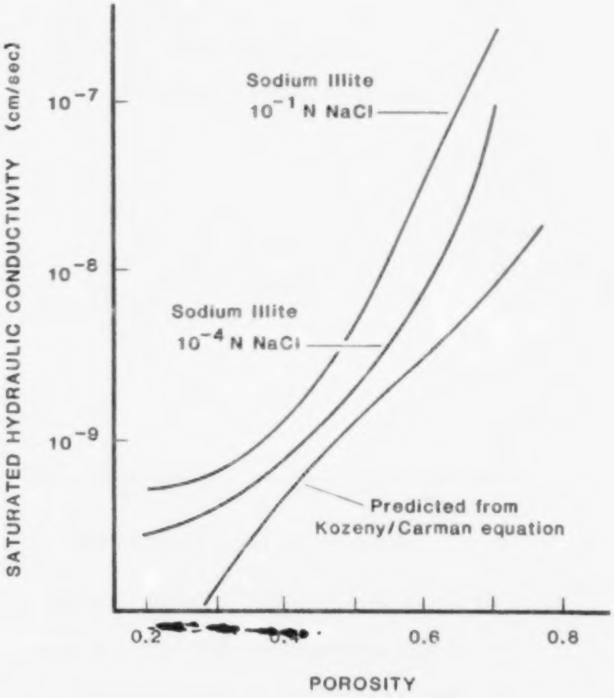


Figure 4.8 Saturated hydraulic flow rates as a function of porosity for illite (Olsen, 1962).

Ratios of measured to predicted values as a function of porosity for several systems are shown in Figure 4.9. Significant points of these plots are: (1) The measured hydaulic conductivity can be greater or less than the predicted value, (2) For compression at porosities greater than about 40 percent, the measured hydraulic conductivity decreases more rapidly with decreasing porosity than predicted, (3) For compression at porosities less than about 40 percent, the measured hydraulic conductivity decreases less rapidly than predicted, and (4) For rebound, the hydraulic conductivity increases less rapidly than predicted (Mitchell, 1976). The major factor responsible for the failure of the Kozeny-Carman equation in fine-textured soils is that the fabrics of such materials do not contain uniform pore sizes (Olsen, 1962). Additionally, Bouma, et al. (1979) point out that it is the connection of the pores and pore path configurations rather than the total number or volume of pores that determines the hydraulic conductivity of fine-textured soils.

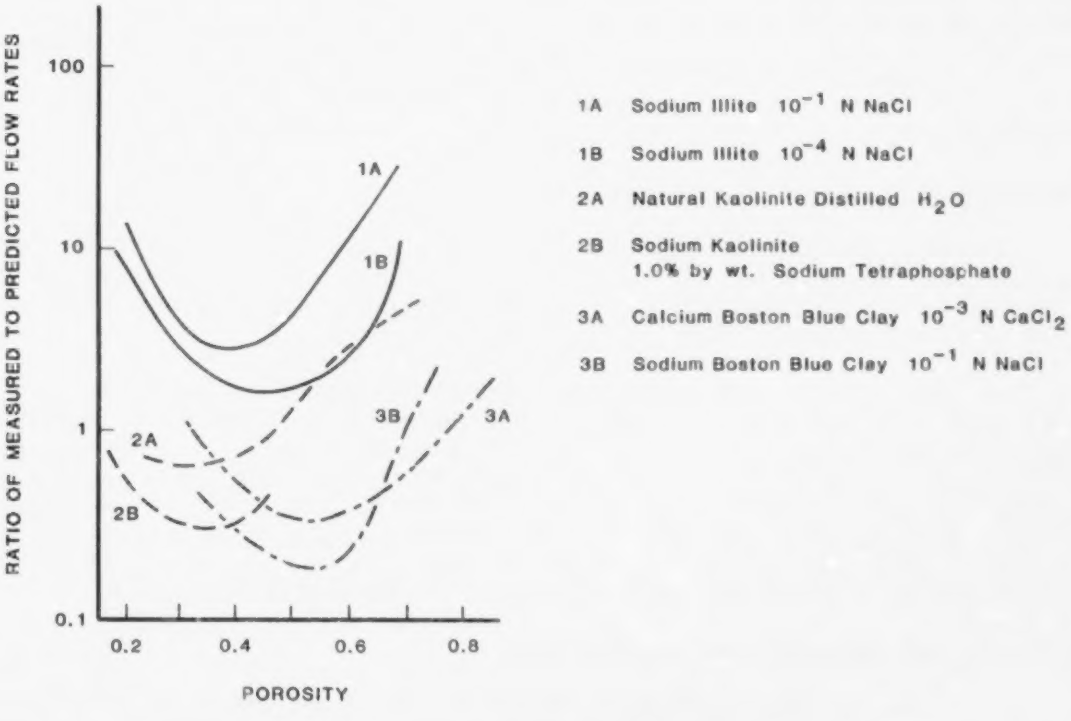


Figure 4.9 Discrepancies between measured and predicted hydraulic conductivities (Olsen, 1962). (a) Compression cycles (b) Rebound cycles

4.3 COMPACTION/HYDRAULIC CONDUCTIVITY TESTING ERRORS

The normal procedure for determination of the hydraulic conductivity of a compacted soil sample is to compact the soil in a mold and then to test for hydraulic conductivity on that sample. The samples so tested are usually cylindrical or disc-shaped with diameters between 3 and 15 centimeters. However, when trying to estimate field hydraulic conductivity from laboratory compaction and hydraulic conductivity testing, there are many sources of error possible during both laboratory compaction procedures as well as during laboratory hydraulic conductivity testing. The types and sources of these errors are discussed below.

Effect of Compaction Water Content

It has been clearly established that hydraulic conductivity of saturated samples is relatively high for samples compacted dry of optimum water content while the hydraulic conductiivity is relatively low for samples compacted wet of optimum water content. Daniel (1981) reported that the hydraulic conductivity of soils compacted dry of optimum might typically be 10 to 1000 times larger than the hydraulic conductivity of soil compacted wet of optimum. For this reason, gross errors in predicting field hydraulic conductivity from laboratory determinations may occur if the field compaction water content is not as anticipated.

Maximum Size of Soil Aggregates

During laboratory tests, the soil aggregates from the field sample are usually broken down into smaller chunks than exist in the field. Such disturbance of the natural aggregation of soils will influence hydraulic conductivity.

Daniel (1981) reported that during testing of the same soil with maximum aggregate sizes of 3/8 inches, 3/16 inches, and 1/16 inch the hydraulic conductivity of the smallest size class was nearly two orders of magnitude less than the hydraulic conductivity of the largest size class. This implies that if aggregate sizes are much smaller in the laboratory sample than exist in the field, the laboratory tests may determine hydraulic conductivities that are much lower than true field values.

Presence of Deleterious Substances

Similar to the situation with differences in soil aggregate sizes between laboratory specimens and field conditions, the presence of deleterious substances in the field such as roots or rocks or any other material not included in the 3-15 cm laboratory specimen may cause substantial discrepancies between the hydraulic conductivity measured in the laboratory and what will actually occur under field conditions.

Method of Compaction

While most laboratory hydraulic conductivity tests on soils are performed on samples prepared with impact compaction using a drop hammer, such equipment bears no resemblance to any pieces of field compaction machinery.

Figure 4.10 presents a comparison of field and laboratory compaction on the same soil. The figure illustrates the difficulty of choosing a laboratory test that reproduces a given field compaction procedure. The laboratory curves generally yield a somewhat lower optimum water content than the actual field optimum.

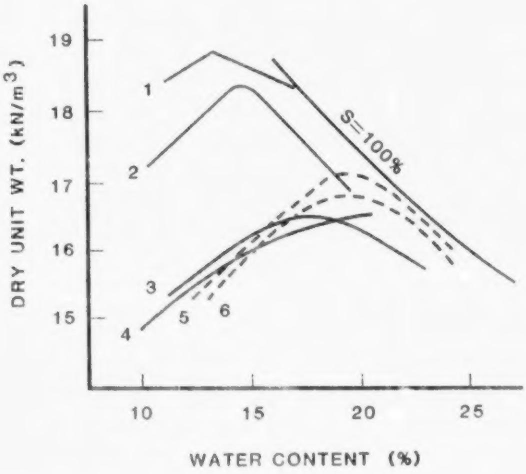


Figure 4.10 Comparison of field and laboratory compaction. (1) Laboratory static compaction, 13.8 MN/m^2 (2) Modified AASHO (3) Standard AASHO (4) Laboratory static compaction 1.38 MN/m^2 (5) Field compaction, rubber-tired load, 6 coverages (6) Field compaction, sheeps-foot roller, 6 passes. Note: Static compaction from top and bottom of soil sample (Lambe and Whitman, 1979).

Additionally, Mitchell et al. (1965) compared static compaction and kneading compaction and reported that similar hydraulic conductivities were found on samples compacted dry of optimum while kneading compaction produced hydraulic conductivities nearly five times less than static compaction when samples were compacted wet of optimum.

Compactive Effort

Many researchers have found that hydraulic conductivity of compacted soils is very sensitive to compactive effort. Mitchell et al. (1965) reported that in studies on compacted silty clay soil that the hydraulic conductivity may decrease by two orders of magnitude, with no change in density or moisture content, simply by changing the compactive effort. Therefore, it is very important to make certain that the compactive effort used in the laboratory is reasonably close to the compactive effort that will be used in the field.

Air in the Sample

In testing compacted samples, it is often assumed that soaking the samples from the bottom, with the top open to the atmosphere, will yield saturated samples. However, Jackson (1963) reported that for loam soils, only 79-91% of the total porosity was fillable by water. Because water cannot pass through air pockets, such pockets will effectively reduce the pore space that can be occupied by water and thus reduce hydraulic conductivity. This phenomena is one of the main reasons why laboratory hydraulic conductivity results are generally lower than hydraulic conductivities under actual field conditions.

Excessive Hydraulic Gradients

It is virtually impossible to duplicate field hydraulic gradients (usually less than 1) in the laboratory as testing time becomes excessive as well as it is difficult to obtain accurate measurements of the low flows and heads associated with very low hydraulic gradients.

Since Darcy's Law indicates a linear relationship between flow rate and hydraulic gradient, many workers have used elevated hydraulic gradients to reduce testing time. However, if hydraulic gradients become excessive, piping or particle migration may occur and adversely affect hydraulic conductivity measurements.

Criteria for selecting an appropriate hydraulic gradient depends on the soil type and the proposed use of the hydraulic conductivity study. In comparative studies where qualitative, rather than quantitative analyses are needed, larger gradients may be used. Wardell and Doynow (1980) used hydraulic gradients of 48 and 67 in a triaxial cell, while Brown and Anderson (1982) utilized hydraulic gradients of 61.1 and 361.6 in a rigid-wall permeameter. In both studies, no piping, particle migration, or non-Darcy behavior was observed.

However, where the objective is to quantitatively estimate field hydraulic conductivity values from laboratory results, Olson and Daniel (1981) have suggested use of hydraulic gradients as close to those encountered in the field as is economically feasible. Likewise, Zimmie et al. (1981) have recommended use of hydraulic gradients of 5-20 (with gradients nearer the lower end of the range to be preferred) for laboratory studies attempting to duplicate field conditions.

Sample Size

The measurement of hydraulic conductivity in small cores offers many practical problems as such cores may not be representative of in situ conditions where root holes, cracks, and fissures are present. Thus, the size of the sample used to test hydraulic conductivity is important if such information is used to predict field behavior.

Anderson and Bouma (1973) experimented with a series of cores of different lengths to determine the effect on hydraulic conductivity. They found that 17 cm long cores had hydraulic conductivities that were half a magnitude less than 5 cm long.

Daniel (1981) measured the hydraulic conductivity of a compacted clay liner on samples of various sizes in the laboratory with one very much larger sample tested in the field. The results were: 3.8 cm diameter core, 1 x 10^{-7} cm sec^{-1}; 6.4 cm diameter core, 8 x 10^{-9} cm sec^{-1}; and 243.8 cm diameter core, 3 x 10^{-5} cm sec^{-1}. Additionally, the average hydraulic conductivity of the liner was back-calculated from measured leakage rates and found to be 1 x 10^{-5} cm sec^{-1}. Such results demonstrate the significance of sample size in predicting field hydraulic conductivity values.

Table 4-2 is a summary of testing errors possible when testing for the hydraulic conductivity of compacted soils (Daniel, 1981). It also shows estimates of the possible magnitude of error associated with each problem and an indication of whether the laboratory hydraulic conductivity is likely to be higher or lower than the field value. The estimates of error are based on available data and are intended to show trends rather than precise values.

TABLE 4-2 SUMMARY OF SOURCES OF ERROR IN ESTIMATING FIELD HYDRAULIC CONDUCTIVITY OF COMPACTED CLAY LINERS FROM LABORATORY TESTS

Potential sources of error	Laboratory K Too High or Low?	Possible Number of Orders of Magnitude of Error
Compaction at a higher water content in laboratory than field	Low	1 to 3
Maximum size of clay chunks smaller in laboratory than field	Low	1 to 2
Deleterious substances present in the field but not in laboratory samples	Low	1 to 3
Use of static or impact compaction rather than kneading compaction to prepare laboratory specimens	High	0 to 1
Use of more compactive effort in the laboratory than in the field	Low	1 to 3
Air in laboratory samples	Low	0 to 1
Use of excessive hydraulic gradients	Low	0 to 1
Sample size	Low	0 to 3

SECTION 5

HYDRAULIC CONDUCTIVITY AND HAZARDOUS WASTE DISPOSAL

Having discussed soil classification, water movement, and soil compaction to provide background information, this section will describe the relevant aspects of hydraulic conductivity to consideration of the different types of hazardous waste disposal faciliftities and their impact on the environment.

5.1 LAND TREATMENT/LANDFARMING

At land treatment facilities the waste material is applied onto the plants and the soil surface or injected into the root zone (Figure 5.1). The major advantage of these types of facilities is in the way that plants and soil can utilize or immobilize water, metals, and contaminants. Additionally, land treatment operations are the only type of waste disposal facility that offer the potential for return to other land uses including agriculture or forestry after waste disposal activities have ceased.

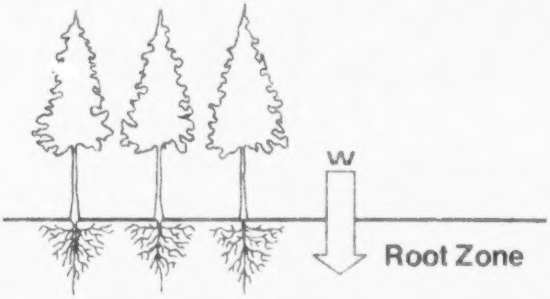


Figure 5.1 Water and waste movement within the root zone.

In land treatment systems considerations of both saturated as well as unsaturated hydraulic conductivity are relevant. Wastewater applied to the soil will infiltrate into and through the soil in accordance with the principles of saturated flow. However, after each application and once the liquid moves lower in the soil profile and root zone, unsaturated conditions and flow phenomena will prevail.

Therefore, when evaluating the feasibilty or developing the design for such a land treatment facility, soil testing for saturated as well as unsaturated hydraulic conductivity may be necessary to predict the behavior of specific soil and site conditions. Specific soil testing methods for accomplishing such tasks are:

Saturated Hydraulic Conductivity Soil Testing Methods

A. Laboratory
    1. Pressure Cells (Section 6, pp. 58)

B. Field
    1. Double Ring Infiltrometer (Section 6, pp. 74)
    2. Air-Entry Permeameter (Section 6, pp. 78)
    3. Cube (Section 6, pp. 81)
    4. Crust (Section 6, pp. 101)

Unsaturated Hydraulic Conductivity Soil Testing Methods
A. Laboratory
    1. Long Column (Section 6, pp. 85)
    2. Instantaneous Profile (Section 6, pp. 90)
    3. Thermocouple Psychrometer 6, pp. 97)

B. Field
    1. Crust (Section 6, pp. 101)
    2. Instantaneous Profile (Section 6, pp. 105)

Because the soil surface and root zone horizons are very accessible and offer the use in situ conditions and larger samples for testing which will more closely represent conditions that will be present at an actual operating site, field testing may be favored over laboratory determinations.

5.2 LANDFILLS AND SURFACE IMPOUNDMENTS

At landfill and surface impoundment facilities the waste material is placed into an excavated pit that can be lined with compacted soil (Figure 5.2). As no soil material is totally impervious, and since such soil liners will have a waste liquid or leachate ponded on top of them, saturated hydraulic conductivity will be the flow regime of interest. Of special note for this particular situation is that a liner developed from disturbed or admixed soil materials will behave differently than soil in its natural state with regard to its hydraulic properties.

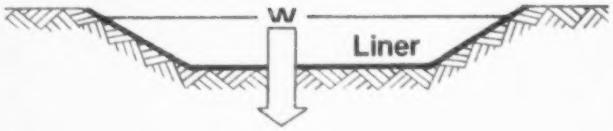


Figure 5.2 Water and waste movement through a soil liner.

Because soil liners are constructed from disturbed or admixed materials, there is no simple and reliable way to test them in situ. Accordingly, hydraulic conductivity must be performed on compacted laboratory specimens that will be used in the field. Therefore, as the facility is constructed, the field density should be checked to ascertain that density and associated hydraulic conductivities are related to the laboratory model.

Laboratory methods for determining saturated hydraulic conductivity on compacted specimens are:

1. Compaction Molds (Section 6, pp. 60)
2. Consolidation Cells (Section 6, pp. 64)
3. Triaxial Apparatus (Section 6, pp. 66)
4. Thermocouple Psychrometers (Section 6, 97)

5.3 THE UNSATURATED ZONE

Another type of liquid movement that is relevant in all types of land disposal facilities is movement in the unsaturated zone between the root zone or liner and ground water table or bedrock as depicted in Figure 5.3.

As described in Section 3, unsaturated hydraulic conductivity is more difficult to measure than saturated hydraulic conductivity due to the fact that the unsaturated hydraulic conductivity varies with both moisture content and pressure head and therefore must be determined over a range of values while saturated hydraulic conductivity will be a constant value.

Also, it can be noted that testing of the unsaturated zone during feasibility and design stages will be of benefit later as for most systems there will be the requirement for monitoring of the unsaturated zone after construction of the facility. Good decisions made during feasibility and design stages for types and locations of unsaturated hydraulic conductivity tests will facilitate the unsaturated zone monitoring requirements.

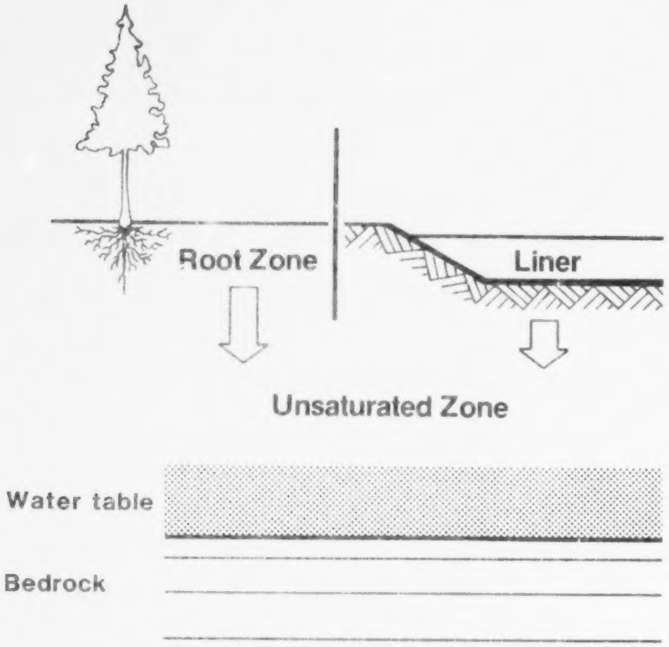


Figure 5.3 Water and waste movement in the unsaturated zone.

Types of tests for determination of unsaturated hydraulic conductivity are:

A. Laboratory Tests
   1. Long Column (Section 6, 58)
   2. Instantaneous Profile (Section 6, 90)
   3. Thermocouple Psychrometers (Section 6, 97)

B. Field Tests
   1. Crust (Section 6, 101)
   2. Instantaneous Profile (Section 6, 105)

5.4 THE SATURATED ZONE

A fourth category of liquid movement that is relevant in most types of land disposal facilities is movement in the unsaturated zone or water table that occurs under a potential waste disposal site. As the saturated zone will often occur at great depths below the soil surface, in situ tests utilizing boreholes will be necessary. Generally, constant or falling head tests will be employed and examples of the variety of approaches are: (1) Augerhole; (2) Cased borehole (no inserts); (3) Cased borehole (with inserts): (i) sand filter plug, (ii) perforated/slotted casing in lowest section, and (iii) well point placed in hole, casing drawn back; (4) Piezometer/permeameters (with or without casing): (i) suction bellows apparatus, (ii) short cell, and (iii) piezometer tip pushed into soft deposits/placed in boring, sealed, casing withdrawn/self-boring; and (5) Well-pumping tests.

As these tests are applicable to testing the saturated zone below a water table, they are not specifically soil testing methods. Rather, they are methods to ascertain the flow rate and direction of the existing ground water. Therefore, such methods are not described in this report, but can be found in most geology/hydrology or engineering texts.

SECTION 6

SOIL TESTING METHODS

6.1 SATURATED HYDRAULIC CONDUCTIVITY

6.1.1 Laboratory Tests

Pressure Cells--

General description-- The pressure cell technique is a method where an undisturbed core, or volume of soil, is placed in a metal pressure cell. After the soil is initially saturated, it is connected to a standpipe where a falling head procedure allows water to move through the pressure cell.

Parameters measured-- Saturated hydraulic conductivity (cm sec^{-1}).

Method-- (Klute, 1965a).

Apparatus: The basic equipment involved is (1) pressure cell, (2) standpipe, and (3) water supply as shown in Figure 6.1

Procedure:

(1) Saturate the soil column.

(2) Connect soil column to end caps containing porous plates.

(3) Fill the standpipe with liquid to a height greater than H_1.

(4) Measure the time for hydraulic head difference to fall from H_1 to H_2.

(5) Measure the cross-sectional area of the standpipe, the temperature of the water, and sample length and diameter.

(6) Calculate the conductivity from

$$K = \frac{al}{At} \ln \frac{H_1}{H_2}$$

where a = cross-section area of standpipe
l = length of soil column
A = cross section area of soil column
t = elapsed time for H_1 to decrease to H_2.

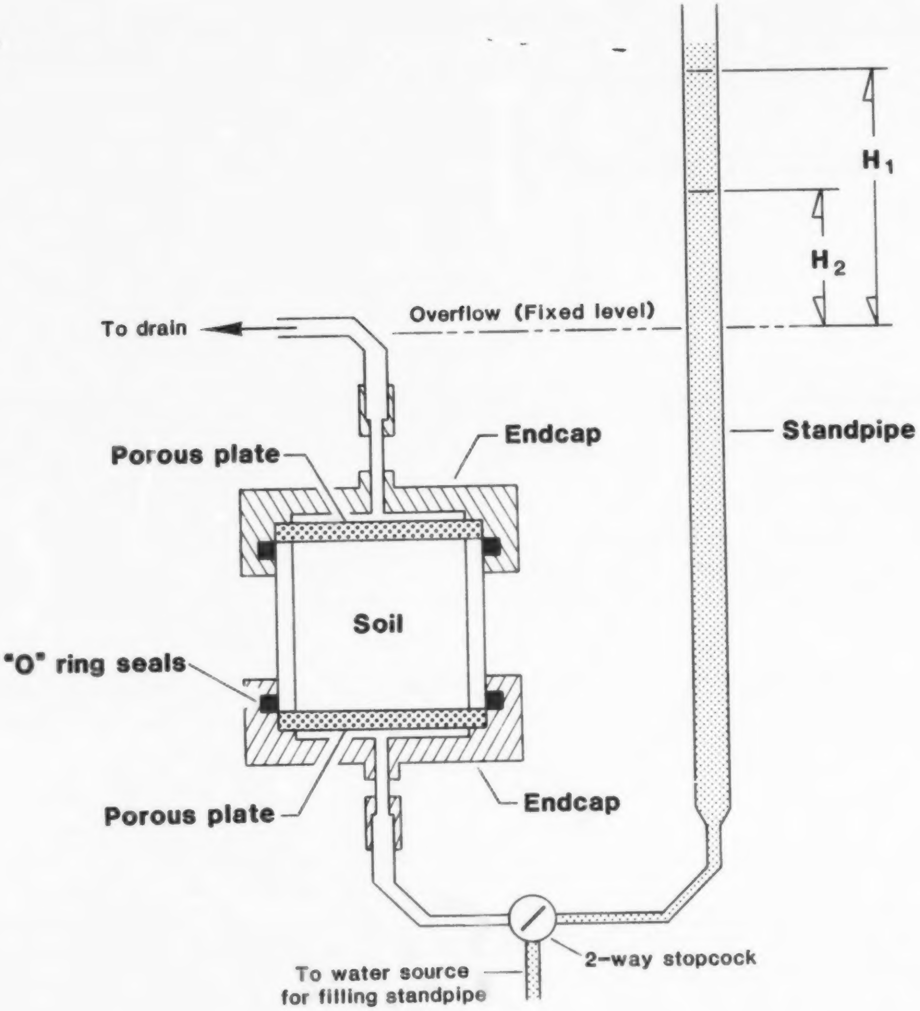


Figure 6.1 Apparatus for pressure cell method (Klute, 1965a).

Precision and Accuracy-- The sampling error involved in hydraulic conductivity measurements of this type has been reported by Mason et al. (1957). An analysis of variance was performed on the conductivity rate measurements and found the variation within a given pit or site ranged from 0.10 to 0.18.

Confidence limits in terms of hydraulic conductivity were computed using a variance of 0.10 and a t-distribution value appropriate to a 95% confidence level. The results are given in Table 6-1. It shows that the confidence interval (ΔK) depends upon the number of samples and upon the mean value of the hydraulic conductivity (K).

TABLE 6-1. CONFIDENCE LIMITS FOR HYDRAULIC CONDUCTIVITY AS A FUNCTION OF NUMBER OF SAMPLES AND THE MEAN CONDUCTIVITY (Mason et al., 1957)

Number of samples	Confidence limit ΔK
2	2.00 K
3	1.90 K
5	1.45 K
8	1.11 K
16	0.76 K

Limitations of test-- (1) Small sample can be unrepresentative of field conditions; (2) Test make take long periods of time on fine-textured or remolded soils; and (3) Saturating the cores by submerging one end in a pan of water with the other end open to the air for 16 hours may not completely saturate the samples. Other saturation techniques include vacuum wetting, fluctuating external gas pressure, and preliminary flushing of the pores with carbon dioxide followed by passage of air-free water (Reeve, 1957).

Status of the method-- This method is the accepted standard test for laboratory determination of saturated hydraulic conductivity in the agricultural sciences.

Compaction Molds--

General description-- The general compaction mold technique is a method where disturbed soil is compacted in a metal cell. This metal cell is then placed in a pan of water to allow for saturation. Then a falling head technique similar to the described method for pressure cells is applied. Differences in the height of the liquid in the standpipe are recorded over time.

However, the method described here is a modified compaction permeameter technique as presented by Matrecon, Inc. which utilizes a constant elevated pressure rather than a falling head to speed up testing time.

Parameters measured-- Saturated intrinsic hydraulic conductivity (cm^2)

Method-- (Matrecon, 1980).

Apparatus: Equipment needed will include: (1) Soil crusher; (2) Soil grinder; (3) 2 mm Sieve; (4) Moisture cans; (5) Balance for up to 20 kgs.; (6) 105°C Drying oven; (7) Compaction molds; (8) Compaction rammer; (9) Steel straight edge; (10) Permeameter bases and top plates; (11) A source of compressed air with a water trap, regulator, and prèssure meter; (12) A fraction collector with automatic timer for collection of samples over time; (13) An airtight, cooled chamber to limit volatile loss of samples during and after sampling; and (14) A vented hood to hold the compaction permeameters and the chamber containing fraction collector (safety precaution).

The modified compaction permeameter is shown in Figure 6.2.

Procedure:

(1) Disaggregate soil and allow to air dry.

(2) Grind the air dried soil and pass it through a 2 mm sieve.

(3) Mix the sieved soil thoroughly and divide into two lots of equal weight. Each lot of soil should be placed in airtight containers at room temperature until time of use. Each lot should consist of enough soil to prepare up to 10 compaction molds (50 kg will provide for some spillage losses assuming a mold volume of about 1000 cm^3).

(4) Use one lot of the soil to determine the moisture density relations of the soil by following the ASTM Method D 698-78. This will determine the optimum moisture content to obtain the maximum density at the compactive effort to be used.

(5) Use a second lot of the soil to prepare compaction molds at optimum moisture content.

(6) Fit a valve on top of the permeameter top plate with pressure fittings and connect it to a source of air pressure via copper tubing. Place a water trap, pressure regulator, and pressure gauge in line between the air pressure source and permeameter. The water trap should go between the pressure source and regulator to prevent buildup of debris on the membrane in the regulator. The pressure gauge should be located between the regulator and a pressure manifold to the permeameters so that the hydraulic head being exerted on the dry cores may be monitored.

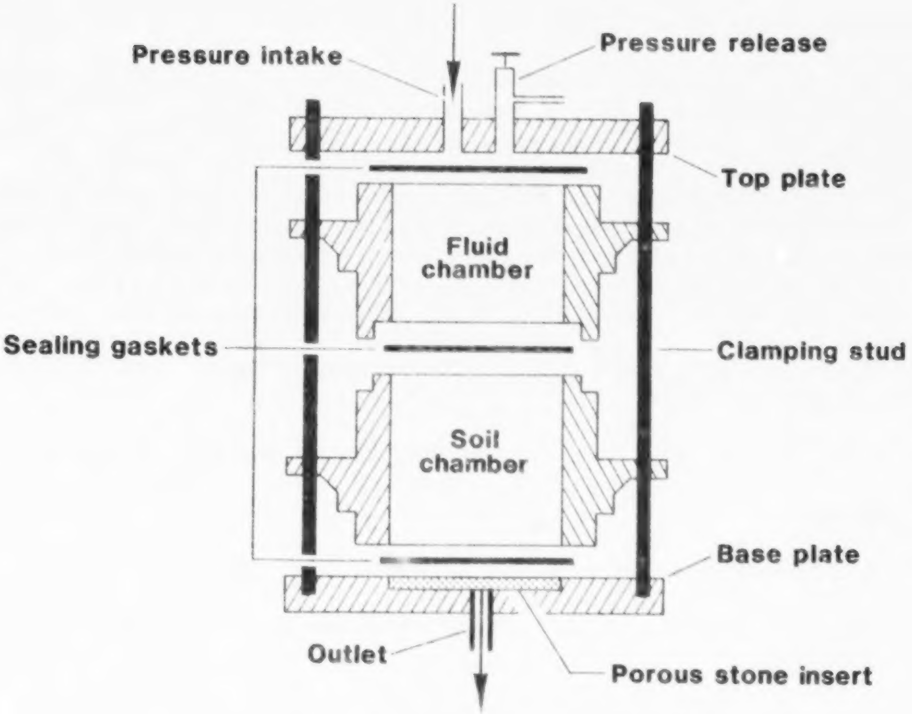


Figure 6.2 Modified compaction permeameter (Matrecon, 1980).

(7) Place sufficient volume of the leaching solution in the chamber above the compacted soil.

(8) Apply pressure to force at least one pore volume of the standard leachate (0.01 N $CaSo_4$ or CaCl) through the dry cores. After the intrinsic hydraulic conductivity values are stable and below 10^{-10} cm^2, release the pressure, disassemble the permeameter, and examine the core.

(9) If the clay core has shrunk, it is unsuitable as a dry liner.

(10) If the clay has expanded into the upper mold, remove the excess soil with a straight edge by cutting so as to not smear the clay surfaces. Reweigh the core to determine its density, then remount it on the permeameter.

(11) Repressurize the permeameter and pass standard leachate through until the intrinsic hydraulic conductivity value stabilizes again below 10^{-10} cm^2.

(12) Remove the remaining standard leachate from eight of the fluid chambers and replace it in duplicate cores with each of the two wastes or waste leachates to be tested.

(13) If, after passage of one pore volume of the various leachates, the intrinsic hydraulic conductivity values of the cores are still below 10^{-10} cm^2, disassemble the permeameter and reexamine the cores.

(14) If the dry core has shrunk, it is unsuitable as a clay liner for that waste.

(15) If the clay core has expanded, repeat step 10, then proceed to step 17.

(16) If the clay has not changed volume, remount it on the permeameter.

(17) Repressurize the permeameter and pass at least one pore volume of the standard leachate. If its intrinsic hydraulic conductivtiy has climbed above 10^{-10} cm^2 (circa 10^{-5} cms^{-1}), the clay is not suitable for containing the waste. If the intrinsic hydraulic conductivity values measured on a waste's primary and secondary leachate have consistently stayed below 10^{-10} cm^2, proceed to Step 18.

(18) Examine the translucent teflon outlet tube for signs of soil particle migration out of the core. If there is evidence of soil migration, pass at least one more pore volume to observe if this internal erosion of the core continues. If it continues after the two pore volumes of standard leachate have passed, the clay is unsuitable for that waste. If the soil migration stops, at least one pore volume of the standard leachate should be passed to assure that the core stabilization is permanent; then proceed to step 19.

(19) If there are no signs of soil migration, depressurize the system and extrude the clay cores from their molds to examine them for signs of cracking, internal erosion, soil piping, clay dissolution, stuctural changes, or any other differences from the control cores (those having received only saturated leachate). If there are no signs that the cores have deteriorated, the clay should be suitable for lining the disposal facility to contain the waste.

The equation used for calculation of the intrinsic hydraulic conductivity (K) is:

$$K = \frac{VnL}{pg\ At\ (L + H)}$$

where K = intrinsic hydraulic conductivity (cm^2)
V = volume of flow (cm^3) in time t
n = permeant viscosity (dyne sec cm^{-1})
p = permeant density (gm cm^{-3})
g = gravitational constant (cm sec^{-2})
A = cross sectional area of flow (cm^2)
t = time (sec)
L = length of soil core (cm)
H = pressure (cm of H_2O).

Precision and accuracy-- Not known.

Limitations of test-- (1) Small sample can be unrepresentative or field conditions; (2) Use of excessive head pressures may produce flow along side walls of permeameter; (3) Potential for interaction between metal cell components and waste; (4) No assurance of sample saturation during test; and (5) Test will take 1 to 5 months.

Status of the method-- Experimental. Recently developed for particular application to use of an actual liquid waste (rather than water) with compacted soil layer.

Consolidation Cells--

General description-- The use of consolidometers is common in the field of geotechnical engineering, to determine the compressibility and rate of settlement of soil. Because consolidation is largely caused by squeezing water out of the soil, it follows that consolidation is a function of hydraulic conductivity. The consolidation cell technique is a method that employs direct measurement by means of a falling head permeameter of special design used in conjunction with a conventional consolidaton apparatus.

Parameters measured-- Saturated hydraulic conductivity (cm sec^{-1}).

Method-- (Means and Parcher, 1963).

Apparatus: The basic equipment involved is (1) fixed-ring consolidation cell, (2) an apparatus for applying the head of water mounted on a board as shown in Figure 6.3.

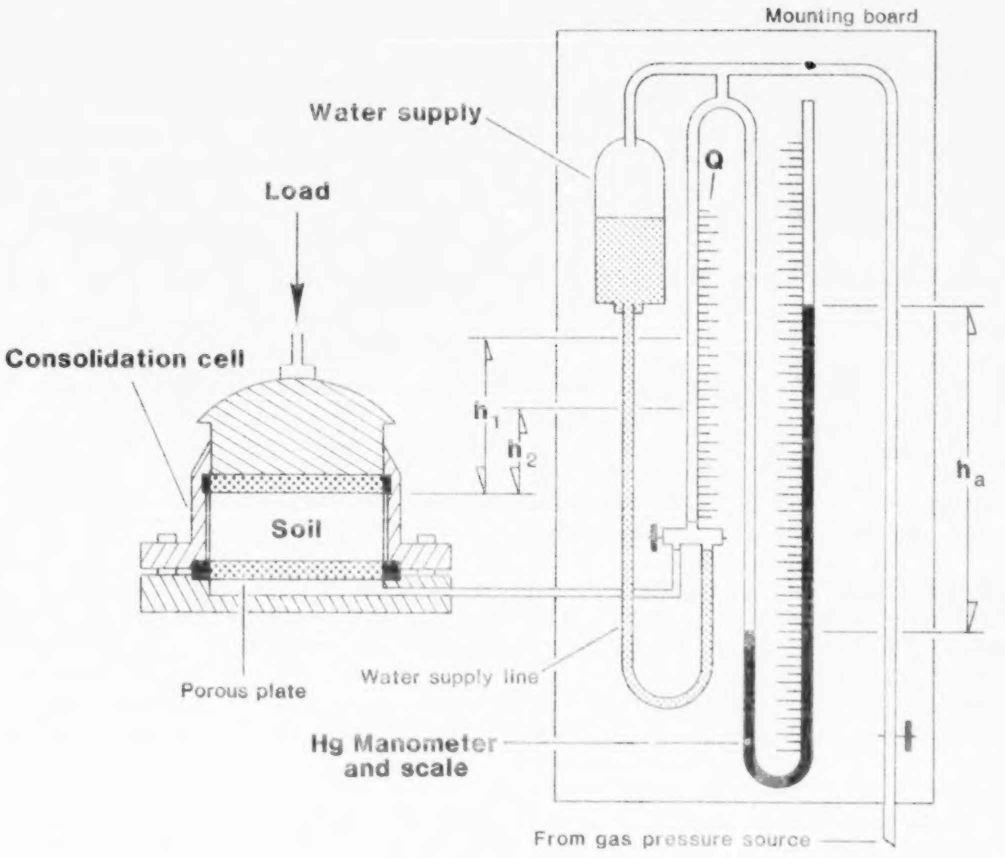


Figure 6.3 Apparatus for hydraulic conductivity in conjunction with consolidation test (Means and Parcher, 1963).

Procedure:

(1) A soil sample is cut to fit snugly into the fluid-ring consolidation cell so there is no leakage between the sample and ring.

(2) Porous plates are placed above and below the sample to allow water to flow freely through the sample.

(3) Water under the applied head is admitted to the bottom of the sample through the lower porous plate and forced upward through the sample. A load is applied to the sample through the upper porous plate. This load should remain long enough to produce complete consolidation under this load.

(4) Add water to the burette.

(5) Record the initial head applied, h_1; the final head, h_2; and the time between the measurements of h_1 and h_2. Since h_1 and h_2 are only a small portion of the total applied head, the test may be considered a constant head test without appreciable error by using $h = (h_1 + h_2)/2 + h_a$.

(6) Determine the hydraulic conductivity from:

$$K = \frac{QL}{hAt}$$

where K = saturated hydraulic conductivity (cm $\sec^{-1}$)
Q = flow (cm^3)
L = length of sample (cm)
h = head (cm)
A = cross sectional area of sample (cm^{-2})
t = time (sec)

Precision and accuracy-- While precision and accuracy of this method are not specifically known, it has been concluded (Zimmie et al., 1979) that direct measurement of hydraulic conductivity of a consolidated sample is much more precise than calculating hydraulic conductivity from consolidation theory using the coefficients of consolidation and compressibility along with void ratio.

Limitations of test-- (1) Small samples can be unrepresentative of field conditions; (2) falling-head procedure may take long periods for measurement of hydraulic conductivity in clay soils; and (3) sample saturation cannot be assured.

Status of the method-- The consolidaton cell method is routinely used for other engineering consolidation-hydraulic conductivity problems such as earth dams, retaining walls, slurry trenches, etc. The method has not been widely used in the evaluation of soil and waste disposal problems.

Modified Triaxial Apparatus--

General description-- The modified triaxial apparatus technique is a method where the key elements are a soil specimen surrounded by a thin, flexible rubber membrane enclosed in a fluid pressurized chamber. By the application of the proper chamber pressure and vertical load on the piston, the specimen can be stressed to in situ conditions. Drain holes at both ends of the specimen allow the performance of hydraulic conductivity tests.

Parameters measured-- Saturated hydraulic conductivity (cm sec^{-1}).

Method-- (Wardell and Doynow, 1980).

Apparatus: The triaxial cell is a standard low pressure cell which utilizes 1.4 inch diameter samples. The cell base is equipped with four drain holes each of which leads externally to a no-volume change valve. Two of these drains lead vertically into the base of the sample, with one used for applying back-pressure while the other is used for measuring the amount of outflow. A third drain is the duct for the confining liquid. The fourth drain is connected to the top cap which is placed on top of the soil sample and is used for applying back-pressure and to impose the head of water during actual hydraulic conductivity testing.

A schematic diagram of the triaxial testing apparatus is shown in Figure 6.4. The chamber fluid is pressurized by applying air pressure to the water in tank 1. The actual pressure is measured roughly using a pressure guage (PG 1), and more accurately with a mercury manometer (M1). The fluid going to the top and bottom caps of the soil sample is also pressurized with air and the pressure measured with a mercury manometer (M2). The water in tank 2 is de-aired. Using a series of three valves (V6, V7, V8), it is easy to direct the de-aired water in all the possible flow paths. For example, pressure can be applied to the bottom of the sample with the vacuum on the top for saturation; pressure can be applied to both top and bottom to dissolve air into the water (back-pressure); or hydraulic conductivity measurements can be made with flow upwards or downwards. For testing, the water flows downwards to atmospheric pressure and is measured using a standpipe with a diameter of approximately 0.11 cm.

Procedure:

(1) The disturbed sample material is oven-dried at 105°C, and then ground up to pass a number 200 sieve.

(2) The sample is prepared by mixing 1500 ml of de-aired water with six pounds of clay. The water is added slowly, with each amount being mixed by hand into a slurry, making sure the clay has absorbed all of the water.

(3) When the clay has a uniform consistency, it is placed into a large Proctor mold that has holes in the base to allow water to enter or exit.

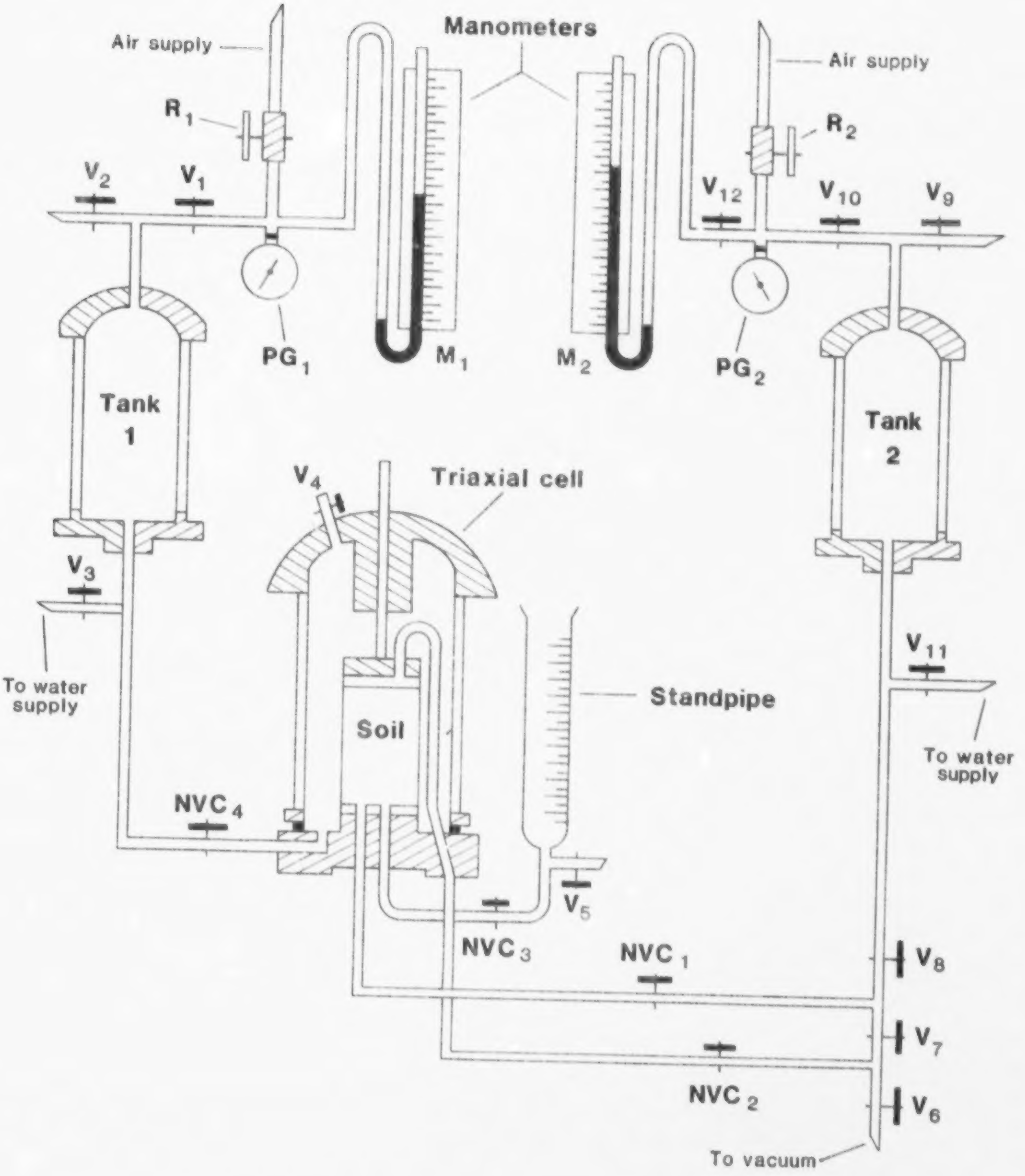


Figure 6.4 Schematic of modified triaxial apparatus (Wardell and Doynow, 1980).

(4) A piston with a similar hole pattern is placed on top of the sample. Filter paper is placed on both top and bottom of the sample to prevent the pore spaces from clogging. The mold is placed in a pan to ensure that

the mold had a large supply of water during consolidation. The pan is filled with de-aired water at all times.

(5) The Proctor mold is placed in a consolidation frame and weights are applied slowly to the lever arm to allow the sample to consolidate, and to limit the amount of soil squeezing out the top and sides of the piston.

(6) Weights are added until the sample has an equivalent overburden pressure of 30 psi and then the sample is allowed to sit for three days to ensure full consolidation.

(7) The sample is then taken out of the consolidation frame and cut and prepared according to triaxial procedures given by Bishop and Henkel (1962).

(8) The sample is loaded into the triaxial cell and surrounded by a standard rubber membrane (0.008 inches thick).

(9) After loading the sample into the triaxial apparatus, a chamber pressure of 14 psi is applied to approximate the low overburden pressure of typical hazardous waste disposal sites as fifteen feet of overburden which would be approximately equal to 14 psi. After application of the chamber pressure, the drains are closed.

(10) Then backpressure is applied to fully saturate the sample. To apply backpressure, chamber pressure and backpressure have to be raised simultaneously. The backpressure and chamber pressure are increased the same at all times. The pressures are increased in 5 psi increments and allowed to remain at that pressure for five minutes. After the five minute period, the pressure is raised until the backpressure reached 30 psi and the chamber pressure is 44 psi. The specimen is allowed to sit overnight.

(11) To initiate the hydraulic conductivity test, a head of de-aired water is applied to the top of the sample and a pressure gradient of 5-20 is superimposed. At the same time the valve to the standpipe is opened to allow measurement of the flow volumes.

(12) Immediately after the gradient is applied, the flow rate will be due to a combination of both consolidation and seepage. However, after 15-30 minutes, consolidation effects are negligible. Therefore, hydraulic conductivity values should be determined from data obtained after 30 minutes.

(13) For determination of hydraulic conductivity, equations for constant head tests are used:

$$K = \frac{QL}{hAt}$$

where K = saturated hydraulic conductivity (cm $\sec^{-1}$)
Q = flow (cm^3)
L = length of sample (cm)
h = head (cm)
A = cross-sectional area of sample (cm^2)
t = time (sec)

Precision and accuracy-- Work by Wardell and Doynow (1980) demonstrates results that were reproducable and consistent on the same soil under different hydraulic gradients which would indicate good precision of the method. Also, Zimmie (1981) stated that satisfactory precision can be obtained by using good laboratory techniques, typically within 10-30 percent.

Limitations of test-- (1) Small samples can be unrepresentative of field conditions; and (2) Hydraulic gradients used in connection with this method should be limited to the range of 5-20 (Zimmie, 1981).

Status of the method-- While triaxial apparati are common testing devices used by geotechnical engineers for the measurement ot soil strength, with modifications the device can also be used for measurement of hydraulic conductivity. Presently, this method is probably the most common technique used for the determination of the low hydraulic conductivity of fine-textured soils.

6.1.2 Field Tests

Piezometers--

General description-- The piezometer method is based on the measurement of flow into an unlined cavity at the lower end of a lined hole. Water entering the unlined cavity and rising in the lined hole is removed several times by pumping or bailing to flush the soil pores along the cavity wall. After flushing is completed, the water is allowed to come to equilibrium with the water table.

It should be noted here that there are several varieties of "piezometer" tests used, depending on the geometry and materials located at the point of measurement. Besides the cylindrical cavity outlined in this procedure, there are spherical cavities, sand-filled cavities, piezometer tips placed in sand-filled cavities, or piezometer tips pushed directly into the soil. This last method (Jezequel and Mieussens, 1975) looks especially promising for evaluation of the low conductivities of clay soils.

Parameters measured-- Saturated hydraulic conductivity (cm sec^{-1}).

Method-- (Boersma, 1965a).

Apparatus: (1) Auger: open-blade type; (2) Bailer or pump: tubing diameter smaller than that of the hole, with a check-valve at the lower end; (3) Probe: a measuring tape attached to a float that will fit the auger hole without touching the sides; (4) Stop watch; and (5) Liner: a section of pipe that will fit tightly in the auger hole should be used. The length of such pipe should be sufficient to extend from the bottom of the auger hole to 15 cm or more above the soil surface. This apparatus set-up is shown in Figure 6.5.

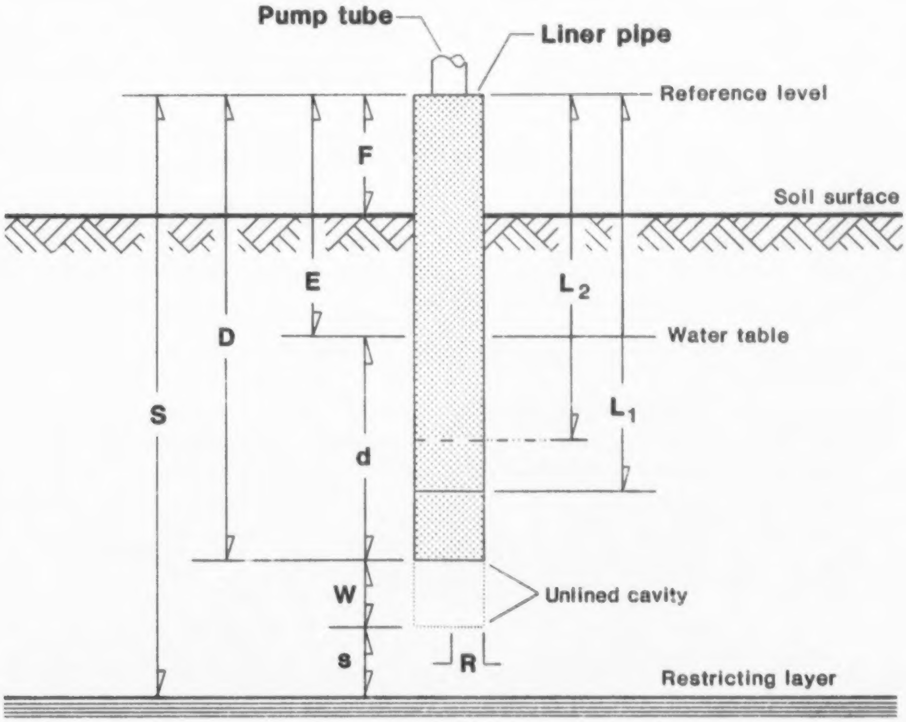


Figure 6.5 Apparatus set-up for piezometer method (Boersma, 1965a)

Procedure:

(1) Remove surface sod, trash, and loose soil from location of the hole.

(2) Install the piezometer. Note: Piezometers are installed by either driving by force or jetting with a stream of water. In general, the driving method is limited to relatively shallow depths (30 feet), whereas piezometers may be jetted to depths of 100 to 150 feet or greater. In this procedure the driving method is used with a 4.9 cm auger and a 5.08 cm liner of electrical conduit.

(3) Auger the hole 10 cm into the soil, remove the auger, and tap the sharpened end of the liner into the hole to the depth of the opening.

(4) Insert the auger into the liner, bore the hole 15 cm deeper, and tap the liner down to the bottom of the hole.

(5) Repeat this process until the bottom of the liner is at the desired depth below the water table.

(6) Then carefully auger out a cavity 10.2 cm in length below the end of the liner.

(7) Remove the water from the hole several times to reduce or eliminate puddling effects.

(8) While removing water, estimate the order of magnitude of the rate of rise for selection of increments of rise to be used in the measurements.

(9) Record the following measurements:

length of piezometer (D)
height of piezometer above ground surface (F)
depth to water table (E)
cavity depth (W)
cavity radius (R)
depth of piezometer below soil surface (H=D-F)
depth of water table (d=D-E).

(10) Remove the water from the pipe, and measure the time Δt required for the water level to rise through the distance Δh. If time permits, make three or more such pairs of measurements as the water rises. Make no measurements after the water has risen to a level 20 cm below the water table.

(11) Repeat the measurement of rate of rise of the water level in the same hole after the water level in the hole has risen to the level of the water table. If values of $\Delta h/\Delta t$ obtained in the second series of measurements are not consistent with those of the first, repeat the process until consistent results are obtained.

(12) To calculate hydraulic conductivity:

$$K = \frac{\pi R^2}{A\Delta t} \ln \frac{L_1-E}{L_2-E}$$

where K = hydraulic conductivity (cm sec^{-1}),
R = inside radius of liner (cm),
E = distance from top of liner to the water table (cm),
L_1 = distance (cm) from top of liner to water level in liner at time t_1,
L_2 = distance (cm) from top of liner to water level in liner at time t_2,
Δt = t_2-t_1, time increment for water to rise from L_1 to L_2 (sec), and
A = geometry factor (cm) which is a function of R, the distance (d) from the water table to the bottom of the liner, the distance (W) from the bottom of the liner to the bottom of the hole, and the distances from the bottom of the hole to a restricting layer.

In this particular case, with W $\doteq$ 10.2 cm and R = 2.45 cm, the A-factor is assumed to be constant and equal to 43.2 cm. Also, considering these same particular cavity dimensions, a nomograph such as shown in Figure 6.6 can be used to determine K.

Precision and accuracy-- For the procedure given, an error less than ± 8% is introduced by assuming A = 43.2 cm, as long as $d > W$ and $S > 1/2\ W$ (Boersma, 1965a).

Limitations of test-- (1) Occurence of errors and inconsistencies due to smear adjacent to the piezometer pocket and air in the piezometer pocket; (2) Only applicable to conductivity measurement below water table; and (3) Measures both vertical and horizontal conductivity. If the diameter of the cavity is small and the length of the cavity is several times its diameter, the horizontal permeability is measured. The wider the hole and the shorter the length of the cavity, the more nearly the measurement becomes one of vertical conductivity.

Status of the method-- The piezometer methods of measuring hydraulic conductivity are the standard methods used when determining water flow rates in shallow ground water areas.

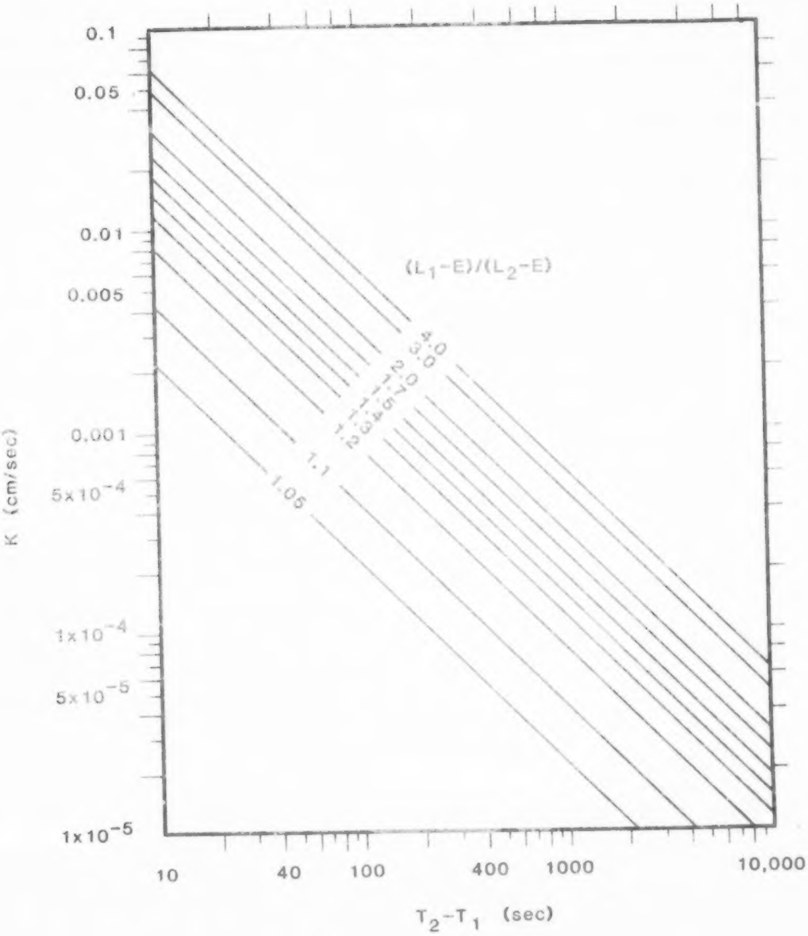


Figure 6.6 Nomograph for the determination of the hydraulic conductivity from data obtained by the piezometer method (Boersma, 1965a). The nomograph is valid only for conditions where the length of the cavity is 10.2 cm and the diameter is 4.9 cm.

Double Ring Infiltrometer/Permeameter--

General description-- The double ring infiltrometer technique is a method where two open metal cylinders, (from a few centimeters to several feet in size), are placed one inside the other, then are driven into the soil and partially filled with water that is maintained at a constant level in both rings. The amount of water added to maintain the constant water level is the measure of the volume of water that infiltrates the soil. This volume can be measured over time and thus be expressed in cm sec^{-1}.

A modification of this method is the permeameter method reported by Boersma (1965b). In this technique, the sides of a hole are used as the outer ring with a smaller metal cylinder positioned in the center. There is a constant water supply system that maintains the water level in the cylinder and in the surrounding hole. This method also employs the use of tensiometers to indicate saturated conditions.

Parameters measured-- Saturated hydraulic conductivity (cm sec^{-1}).

Method I-- Double ring infiltrometer (Bertrand, 1965; ASTM D 3385-75).

Apparatus: (1) Infiltrometer rings: cylinders of cold-rolled steel, aluminum alloy, or galvanized steel with the bottom edge beveled to facilitate driving into soil (15-45 cm in diamaters); (2) Driving plate: a steel plate larger than the largest ring cylinder; (3) Driving hammer: a sledge hammer or other device to tamp on plate to drive cylinder into ground; (4) Water supply: 5-gallon jugs to 55-gallon drums may be used; (5) Puddling protection device: a piece of folded burlap, cloth, heavy paper, or any other suitable material used to protect the soil surface from puddling when water is first added; (6) Timing device, and (7) Depth gauge: a hook gauge, steel tape, rule, or length of heavy wire pointed on one end, for use in measuring and controlling the depth of water (head) in the infiltrometer ring. A manometer could also be used. Figure 6.7 shows the set-up of the double rings, excluding the water supply.

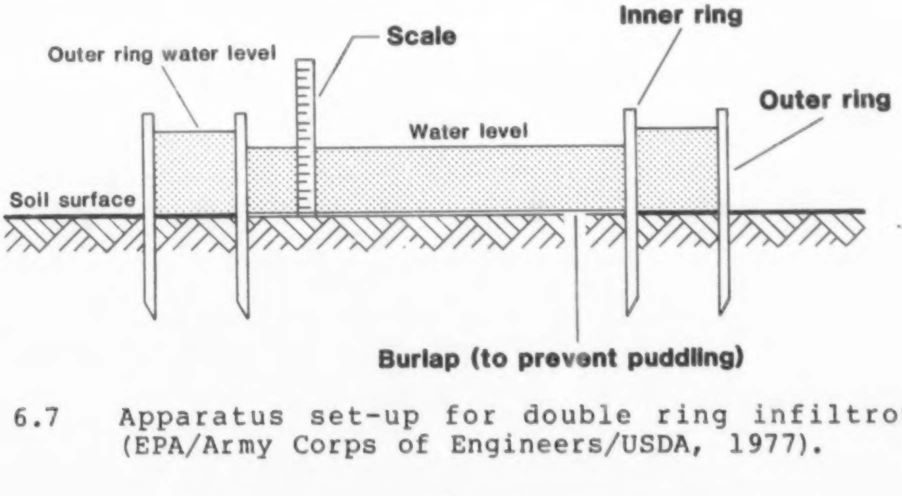


Figure 6.7 Apparatus set-up for double ring infiltrometer (EPA/Army Corps of Engineers/USDA, 1977).

Procedure:

(1) Set outside cylinder in place and push it firmly into the soil. Place the driving plate on the cylinder and use the driving hammer to push cylinder 10-15 cm into the soil.

(2) Repeat step 1 for the smaller ring centered in the outer ring.

(3) Place burlap or other puddling protection material on the soil within the inner cylinder.

(4) Add water to outer ring to a depth of 5-10 cm and maintain this depth throughout the observation period.

(5) Add water to outer ring to a depth of 5-10 cm and maintain this depth after each observation period. Record all volumes of water that are added to maintain a constant head.

(6) Record water volumes used at 15 minute intervals for the first hour, 30 minute intervals for the second hour, and hourly after that until two or more hourly volume measurements are equal.

(7) Calculate the hydraulic conductivity by:

$$K = \frac{V}{At}$$

where
V = volume of water (cm^3)
A = area of inner ring (cm^2)
t = time (sec)

Method II Permeameter (Boersma, 1956b).

Apparatus: (1) Infiltrometer ring: same as for the double ring using larger diameter ring (45 cm); (2) Driving plate; (3) Driving hammer; (4) Water supply; (5) Depth controlling device: a hook gauge, manometer, constant level float valve, or any other apparatus to maintain constant head in ring, and (6) Tensiometers: four mercury tensiometers that are capable of measuring both positive and negative pressures.

This apparatus is shown in Figure 6.8.

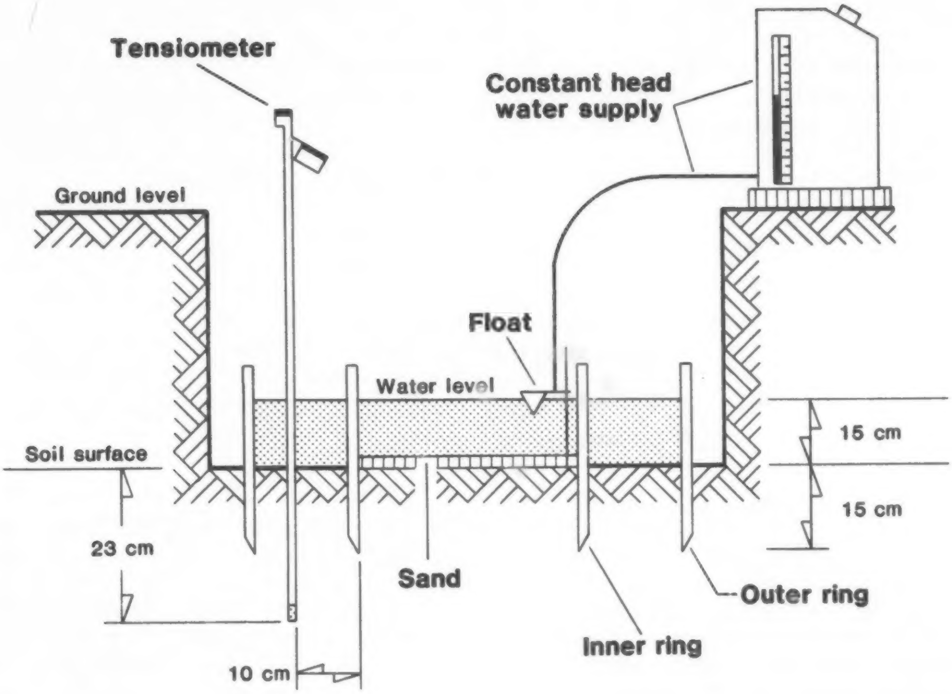


Figure 6.8 Schematic diagram of equipment for permeameter method in place (Boersma, 1965b).

Procedure:

(1) Excavate a hole 1 m square to the horizon to be tested.

(2) Set cylinder in place and push firmly into the soil. Place the driving plate on the cylinder and use the driving hammer to push cylinder 15 cm into the soil.

(3) Spread about 2 cm of uniform, coarse sand over the area inside the cylinder to avoid puddling of the soil surface during the test.

(4) Space the four tensiometers at equal intervals around the cylinder, each 10 cm outside the cylinder and 23 cm below the level of the soil inside the cylinder.

(5) Install the depth-controlling device to maintain a constant 15 cm head.

(6) Add water to inside and outside ring to a depth of 15 cm.

(7) Record the time intervals and water volumes.

(8) Terminate the test when the tensiometers indicate zero tension, and the water is moving through the test layer at a constant rate.

(9) Calculate the hydraulic conductivity from:

$$K = \frac{QL}{AH}$$

where Q = flow rate ($cm^3\ sec^{-1}$)
L = length of soil column inside the cylinder (cm)
A = cross-sectional area of cylinder (cm^2)
H = height of the water level inside the cylinder above the base (cm).

Precision and accuracy-- From the work of Luxmoore, et al. (1981) with double ring tests on a low level radioactive waste disposal site, they reported the infiltration rate of the control treatment to be 3.0×10^{-5} cm sec^{-1} after 20 days, and 3.35×10^{-5} cm sec^{-1} after 259 days. Such results demonstrate that the method offers reproducibility and good precision. However, information on the accuracy of the method for fine-textured soils, or comparison of the double ring method to other methods, is not available.

Limitations of test-- (1) Care must be exercised in the installation of ring cylinders to prevent shatter or compaction of soil adjacent to border. (2) Air may become trapped below the advancing water front which may have significant effect on results obtained. (3) A considerable amount of time may be required for fine-textured soils, and (4) Correction for evaporation should be made.

Status of the method-- (1) Double ring method is ASTM Standard D 3385-75. (2) Permeameter method's extent of use is not known.

Modified Air-Entry Permeameter--

General description-- The air-entry permeameter technique is a method where a 25 cm diameter cylindrical unit of undisturbed soil is isolated within an infiltration cylinder driven into the soil, and a head of water is applied to the upper end of the soil unit, causing water to penetrate the soil with a wetting front. The infiltration rate is measured until the wetting front is close to the bottom of the cylinder which is determined by use of an implanted tensiometer.

Parameters measured-- Saturated hydraulic conductivity (cm sec^{-1}).

Method-- (Topp and Binns, 1976).

Apparatus: The basic equipment required and the experimental set-up for the air-entry permeameter test are shown in Figure 6.9. The items required are: (1) 25 cm diameter metal cylinder with flange of rolled angle iron with attached foam-rubber gasket; (2) plastic sheeting lid with C-clamps for attachment; (3) Water-supply reservoir; (4) Vacuum gauge; (5) Tensiometer; (6) Air escape valve; and (7) Disk used to dissipate energy of the water stream from the water reservoir.

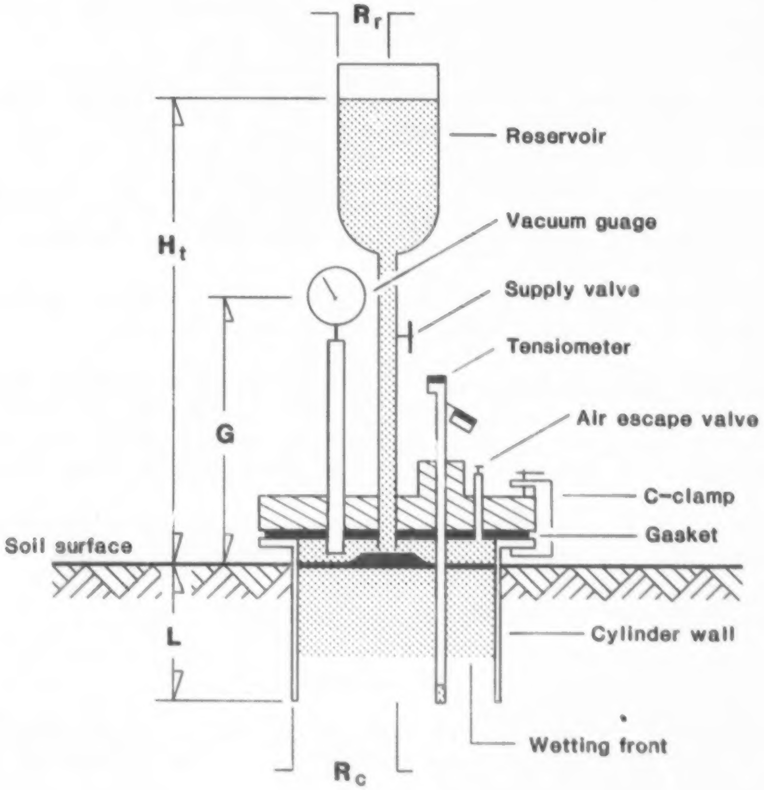


Figure 6.9 Modified air-entry permeameter (Topp and Binns, 1976).

Procedure:

(1) A driver with a sliding weight and cylindrical base is used to drive the cylinder to a predetermined depth.

(2) The soil is lightly packed down against the cylinder wall to ensure a good bond between cylinder and soil.

(3) If the soil is bare, it should be covered with coarse sand to act as a protective layer.

(4) A disk is then placed in the center of the cylinder to dissipate the energy of the water stream from the supply pipe.

(5) The lid assembly with the air valve open and the gauge and supply valves closed is positioned on the cylinder so that the air-escape valve is at the highest point.

(6) The lid is tightened with the C-clamps and lead weights are placed on the lid to offset the hydrostatic lift that will be developed by the elevation of the water-supply reservoir.

(7) The tensiometer is inserted through a 8 cm long guide in the lid of the permeameter.

(8) The water reservoir is filled and the supply line is opened to quickly fill the apparatus while air is allowed to move out of the air-escape valve.

(9) Once the apparatus is filled with water and all air is removed the air escape valve is closed.

(10) Immediately after the air valve is closed, the measurement of the rate of flow of water from the reservoir is initiated and continued until the wetting front causes the tensiometer reading to decrease toward zero.

(11) The water supply valve is then closed and the air-entry pressure is determined on the vacuum gauge.

(12) The air entry valve is calculated from:

$$P_a = P_{min} + G + L$$

where P_a = air entry value of soil, expressed as pressure head in cm water at point of air entry

P_{min} = minimum pressure head in cm water as determined by the maximum reading on the vacuum gauge

G = height of gauge above soil surface in cm

L = depth of wet front (depth of tensiometer) in cm

(13) Saturated hydraulic conductivity is then calculated from:

$$K = \frac{2\ (dH/dt)\ L\ (Rr/Rc)^2}{Ht + L + \frac{1}{2}(Pa)}$$

where $\frac{dH}{dt}$ = rate of fall of water level in reservoir just before closing supply valve, in cm sec^{-1}

Ht = height above soil surface of water level in reservoir at time supply valve is closed, in cm.

Rr = radius of reservoir in cm.

Rc = radius of cylinder in cm.

Precision and accuracy-- Topp and Binns (1976) found that the air-entry permeameter gave reproducible values of hydraulic conductivity at various depth[illegible] in a number of different soils. In comparison with other meth[illegible] they found that results were consistent with values obtai[illegible]rom determinations made on laboratory cores, although [illegible]aboratory core result was generally lower than the hydraul[illegible]nductivity determined by the air-entry permeameter which was probably due to lack of worm holes or cracks in the laboratory samples. Topp and Binns (1976) also found that extrapolated results from the crust method compared favorably with the values obtained from the air-entry permeameter. Aldabagh and Beer (1971) found the method to be consistent and reasonable with equipment variability substantially less than the natural variation of soil.

Limitations of test-- (1) Care must be exercised in the installation of cylinder to prevent shatter or compaction of soil adjacent to border; (2) Cannot be performed very adequately on initially wet or nearly saturated soils because the induced wetting front from the addition of water is not very clear or well-defined; (3) Will be difficult on soils with gravel or stones.

Status of the method-- Relatively new method but its use is increasing due to advantage that it takes relatively short time periods (approximately 1 hour) to conduct test.

Cube Method--

General description-- The cube technique is a method for measuring both the vertical and horizontal saturated hydraulic conductivity of a cube of soil (25 x 25 x 25 cm) which is carved out in situ and covered with gypsum. The vertical saturated hydraulic conductivity is measured by infiltrating water into the exposed upper surface and by collecting it below the exposed lower surface of the cube. To obtain horizontal saturated hydraulic conductivity, the cube is then turned. The two previously open surfaces are covered with gypsum, which is removed from the other two vertical sides. These turn into surfaces for percolation after again turning the cube. A vertical saturated hydraulic conductivity is now measured which represents the horizontal saturated hydraulic conductivity of the cube in its original position in the soil. The set-up of the field operation to obtain the cube is shown in Figure 6.10.

Parameters measured-- Saturated hydraulic conductivity (cm sec^{-1}).

Method-- (Bouma and Dekker, 1981).

Apparatus: Basically, the only apparatus is a hinged wooden box with inside dimensions of 35 x 35 x 35 cm along with tools to dig a soil pit, carve a cube, and gypsum.

Procedure:

(1) A soil pit with a pedestal is dug in naturally wet or very moist soil (so that maximum swelling has occurred).

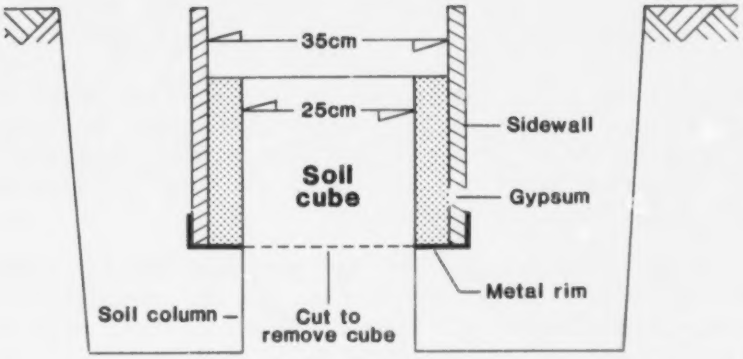
(2) A horizontal plane is exposed and a cube of soil (25 x 25 x 25 cm) is carved out in situ by removing at least 20 cm of soil along its four sides using a sharp knife and removing only small fragments at a time to avoid any compaction of the cube.

(3) The square wooden box that is open at its upper and lower surface is placed around the cube of soil in the pit. A metal rim is attached to the bottom of the box to support the gypsum between the sides of the cube and inner walls of the box.

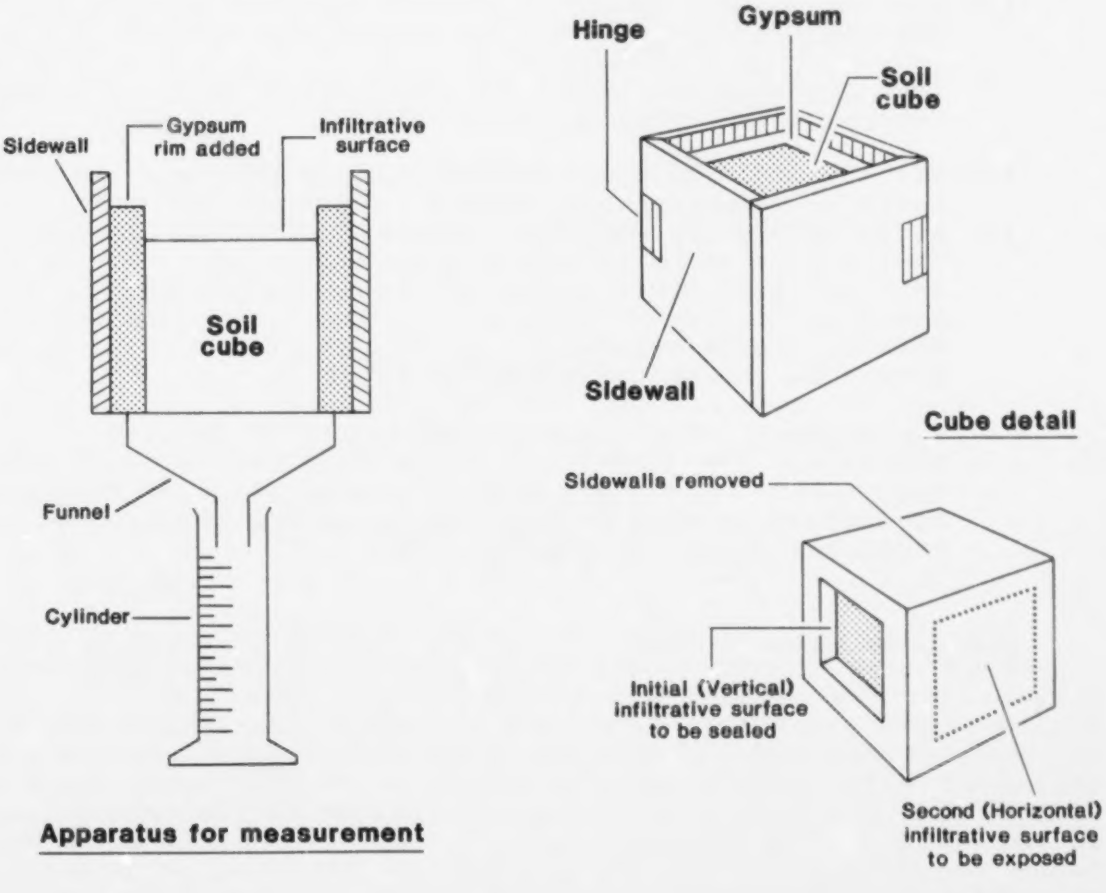
(4) A gypsum slurry is then prepared and poured into this space as soon as its starts to become viscous.

(5) After approximately 20 minutes and when the gypsum has hardened, the box with soil and gypsum is removed from the pit by pulling a metal wire along the outside bottom area of the box.

(6) The upper and lower soil surfaces of the cube in the box are then cleaned and exposed outside the pit by chipping away soil fragments with a small knife.



Excavation and retrieval



Apparatus for measurement

Cube detail

Figure 6.10 Diagram of the cube method.

(7) The box is then placed on a funnel which channels the percolated water to a measuring device.

(8) Then water is shallowly ponded on top of the cube, creating a hydraulic head gradient across the sample close to one. To facilitate such ponding, a small rim of gypsum must be applied on top of the gypsum which already encases the cube.

(9) Fluxes are measured by periodically collecting the percolated volume of water and by considering the cross-sectional area of flow. Such fluxes are identical to saturated hydraulic conductivity, due to the low head on top of the cube.

(10) The measurement is terminated as soon as the fluxes are constant.

(11) The box is now turned on its side and is removed from the gypsum-covered cube by loosening its hinges.

(12) The two exposed sides of the turned cube are then covered with a viscous gypsum slurry.

(13) Two new surfaces for infiltration and drainage are prepared by removing the gypsum covers of the two other sides of the turned cube. Removal should be done such that a 5 cm wide gypsum rim with a height of 5 cm is left on each side which allows ponding on top and supports the cube when it is placed on the funnel. Removal of the gypsum should be initiated by sawing, as knives may cause the gypsum to fracture.

(14) The gypsum-covered cube is now turned 90 degrees and is placed on the funnel to allow the measurement that represents the horizontal saturated hydraulic conductivity of the sample in its original position by repeating Steps (8) through (10).

Precision and accuracy-- While the method is quite new and not widely used presently, its advantages over other methods will provide for its greater use in the future. That is, the cube method offers advantages over other laboratory determinations as the size of the sample is much larger than other methods and therefore will include some macropores as they occur in the field. Also the mode of isolating the sample in the cube method is nondestructive as compared to some field techniques which may cause compaction of the sample due to punching or pounding cylinders or infiltrometers into moist or wet clay soils. Another advantage of the cube method is that both vertical and horizontal saturated hydraulic conductivity are obtained from the same sample. A final advantage of the cube is that the method is very inexpensive and does not require specialized equipment.

Limitations of test-- (1) Method may require relatively long periods of time to perform test on clay soils; (2) Sample saturation cannot be assured; (3) Swelling of sample may occur which may affect hydraulic conductivity measurment.

Status of the method-- Very new method but use will increase due to ease and low expense of procedure.

6.2 UNSATURATED HYDRAULIC CONDUCTIVITY

6.2.1 Laboratory Tests

Steady State--

General description-- Steady state techniques are methods where the hydraulic conductivity is measured by applying a constant hydraulic head difference across the sample contained in a soil core and measuring the resulting steady state flux of water. The flow rate, Q, and tensiometer matric potentials (pressure head) are recorded.

Parameters measured-- Unsaturated hydraulic conductivity (cm sec^{-1}). Apparatus can also be used to determine saturated hydraulic conductivity (see "Pressure Cells", Section 6.1.1).

Method I-- Short column (Klute, 1965b).

Apparatus: A generalized set-up of the equipment required is shown in Figure 6.11. The volume of the soil chamber can vary depending on size and shape of the sample.

This sample core of soil is held between two porous plates, P_1 and P_2, which may be made of plastic, fritted glass beads, cellulose acetate filters, or ceramic. Installed and sealed into the side of this core are two tensiometers, T_1 and T_2. Water is added from a hanging water-column supply system at hydraulic head H_1. Flow occurs through the first porous plate, the soil core (which is maintained at a constant head via a manometer (M)), the lower porous plate, and outflow is via the drip point into a chamber or graduated cylinder.

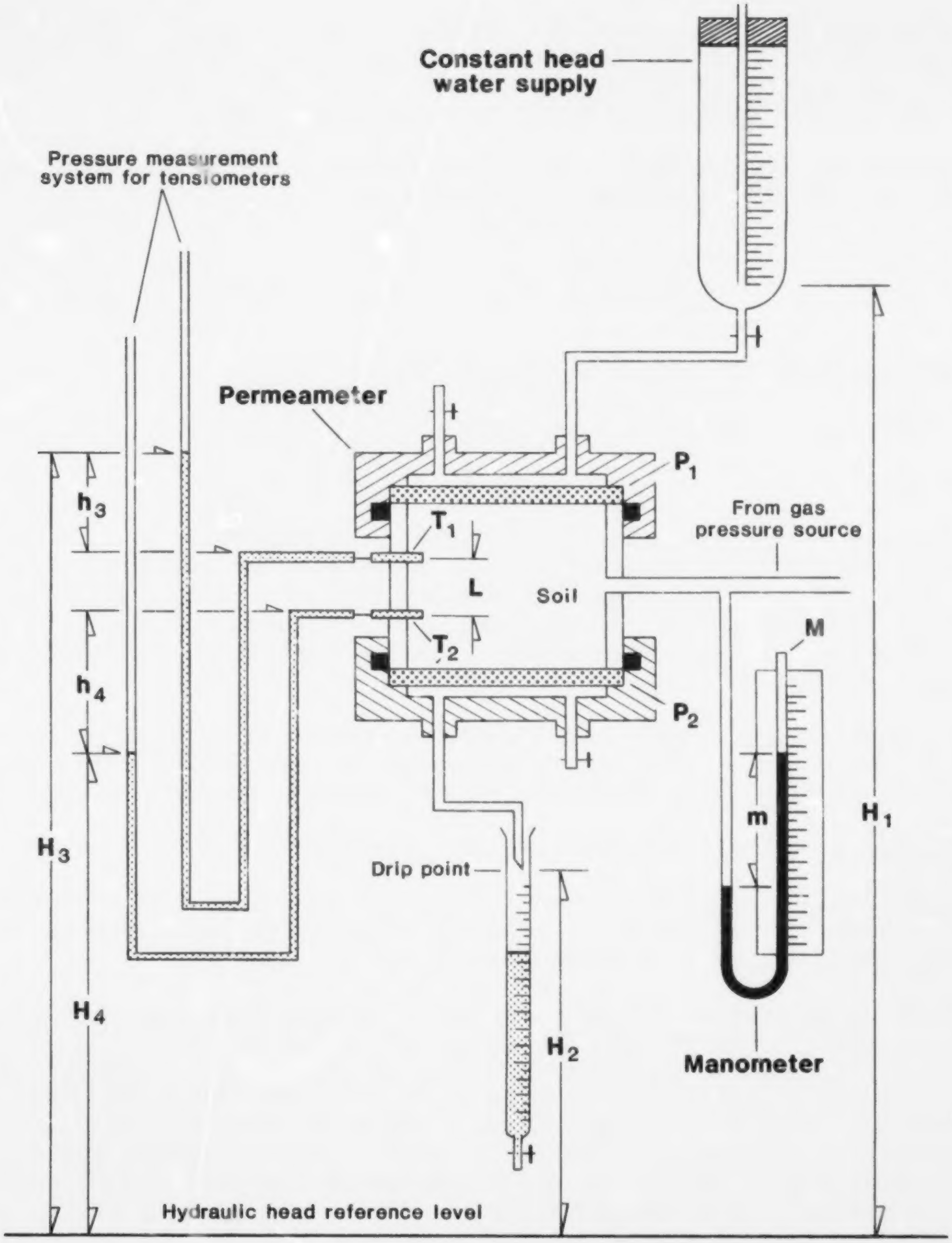


Figure 6.11 Diagram of apparatus for short column steady state method of (Klute, 1965b).

Procedure:

(1) Fill the tensiometers, water supply, and water removal systems with de-aired water by filling them under vacuum or by flushing them following prolonged soaking.

(2) Clamp the sample between the end caps and install the tensiometers.

(3) Measure distance between two tensiometers, L. Calculate cross-sectional area, A, of soil core.

(4) With the outflow tubing clamped off, apply water to wet the sample. Note: It is suggested that 0.01N $CaSO_4$ should be used, and collected outflow should be recycled through core.

(5) When the sample has been wetted, establish a hydraulic gradient across the sample at a mean pressure-head near zero.

(6) Maintain a constant hydraulic head until steady flow is attained. Flow is considered steady state when (1) time-invariant readings of two tensiometers appear, and (2) inflow rates equal outflow rates.

(7) Record the volume of flow, Q, which occurs over time, t.

(8) Record the height of the fluid column of manometer M.

(9) Record the hydraulic heads H_3 and H_4.

(10) Record the pressure heads h_3 and h_4.

(11) Decrease the water content of the sample by increasing the gas pressure on the cell, or by reducing the mean value of H_1 and H_2.

(12) Repeat steps 6 through 11 as needed to obtain information for calculation of the hydraulic conductivity at a series of decreasing pressure heads and water contents.

(13) Maintain a complete record of the volumes of inflow and outflow, as well as the volume of water involved in changes in the readings of the tensiometers.

(14) After the final run through steps 6-11, the soil core should be removed and water content should be determined for the whole sample gravimetrically. This will permit calculation of water content at each mean pressure head from the first water content and volumes of inflow and outflow.

(15) Calculate the hydraulic conductivity at each mean pressure head and water content from:

$$K = \frac{QL}{At(H_3 - H_4)}$$

(16) Calculate the mean pressure head h corresponding to the above conductivity value from:

$$h = \frac{(p_1 m/e) + (h_3 + h_4)}{2}$$

where m is the gauge pressure in the cell expressed as a column of fluid of length m,
p_1 is the density of the manometer fluid,
e is the density of water.

(17) Plot the K(h) function.

Variations: For undisturbed samples, a pressure chamber apparatus similar to Figure 6.12 is used.

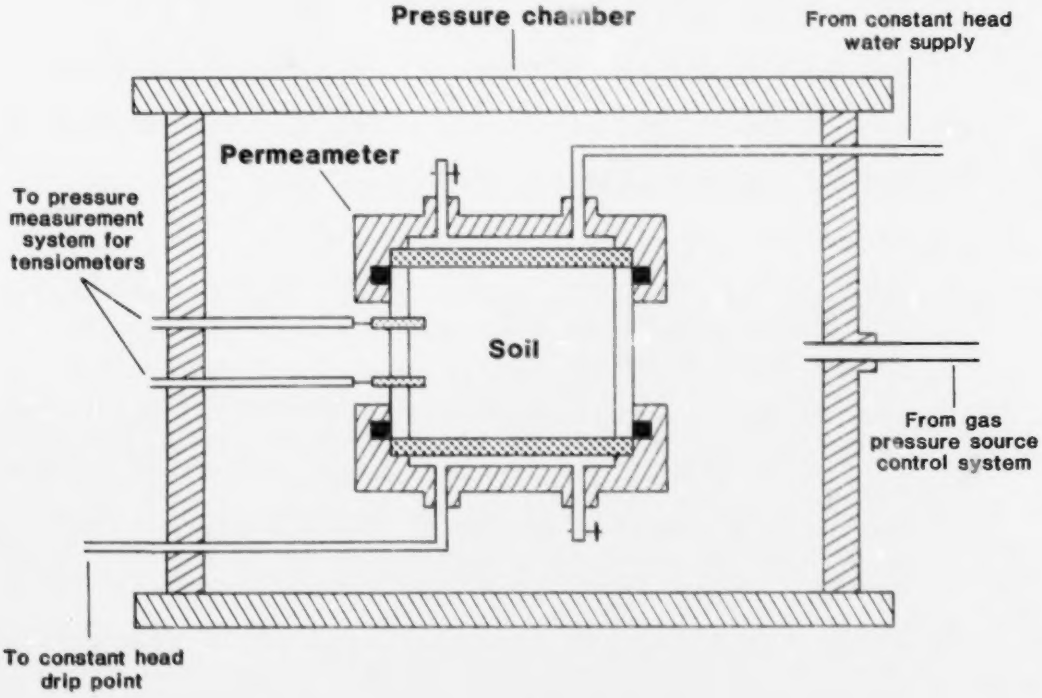

Pressure chamber
From constant head water supply
Permeameter
To pressure measurement system for tensiometers
Soil
From gas pressure source control system
To constant head drip point

Figure 6.12 Alternative steady state method for undisturbed samples (Klute, 1965b).

Method II-- Long column (Klute, 1972).

The long column version of the steady state method uses a column length on the order of 50-200 cm whereas the short columns are on the order of 10-15 cm. Further, more than two tensiometers are encased along the side of the longer column as shown in Figure 6.13.

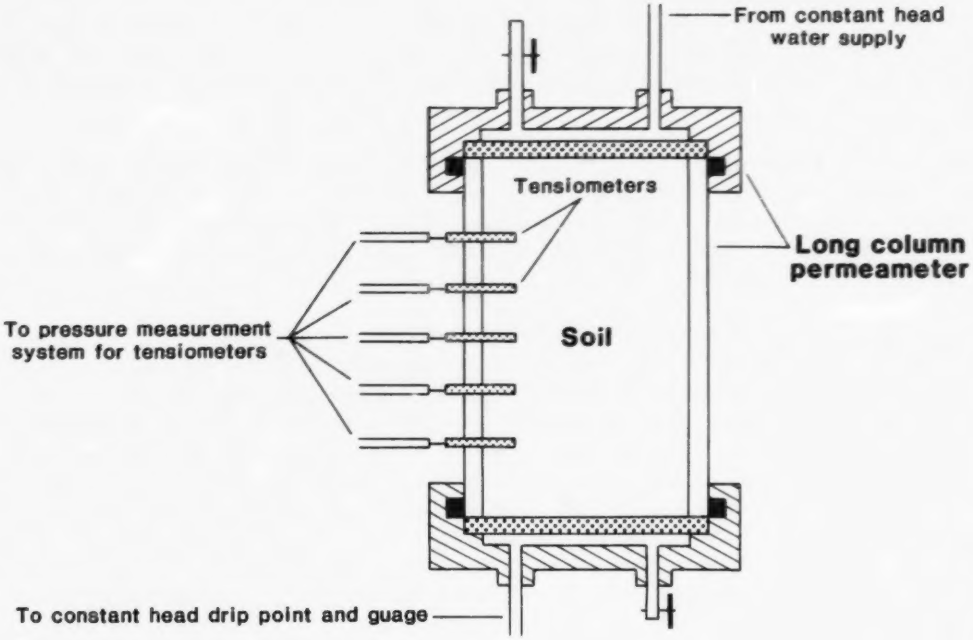

From constant head water supply
Tensiometers
Long column permeameter
To pressure measurement system for tensiometers
Soil
To constant head drip point and guage

Figure 6.13 Diagram of long column version of steady state method (Boersma et al., 1972).

By starting at saturation and proceeding through a series of progressively decreasing flow rates, a series of points can be determined for the drainage K(h) function similar to short column version. An advantage of the long column method is that the use of several tensiometers at convenient intervals along the column will allow the determination of the head difference across each interval and thus the hydraulic conductivity function for each section or layer.

Variations: Watson (1967) describes a long column variation in which a zone of entrapped air (an air lens) is established. The column is initially saturated and steady state flow is used to obtain the saturated conductivity. Then partial drainage is allowed to occur and at an appropriate time water is reapplied at the upper end. This procedure traps a lens of air in the middle of the column. The hydraulic conductivity is calculated in the usual steady state manner.

Another variation in this procedure is water content measurement by gamma attenuation in addition to the pressure head measurements via tensiometry. Thus both the K(h) and K(θ) can be determined from measured values.

Precision and accuracy-- Klute (1965b) states that the variability of results from the short column method will be as large or larger than those from the measurement of hydraulic conductivity of saturated soil by the Pressure Cell method (Table 6-1).

It is believed that a large portion of this variation can be attributed to the length of the core used (SSWMP, 1978). Anderson and Bouma (1973) showed that variation in hydraulic conductivity decreased significantly for cores that were greater than 15 cm in length.

Limitations of test-- (1) Steady state methods require relatively long times to establish steady state flow; (2) Small samples may not be representative of field conditions; (3) The usual steady state procedures yield a hydraulic conductivity pressure head relationship, K(h). If the measurement of the hydraulic conductivity-water content function K(θ) is desired, additional procedures such as gamma attenuation or neutron attenuation will have to be employed to determine water content of the sample at each steady state (or determine water content-pressure head function on separate sample). The short column method outlined could estimate the K(θ) function using final water content and inflow and outflow volumes to back-calculate water contents at each steady state; (4) Hydraulic conductivity versus suction or degree of saturation is established from wet to dry but not dry to wet as will occur at the actual waste site; (5) Maximum suction limited to available range of tensiometer unless pressure offset method can be utilized.

Status of the method-- Since this method can determine both saturated and unsaturated hydraulic conductivity, it is a widely employed procedure by soil physicists who require analysis of steady state conditions (as compared to transient or unsteady state conditions).

Unsteady State: Instantaneous Profile--

General description-- The instantaneous profile technique is a method that can be used in the laboratory or in the field. In the laboratory, a flow system (usually a soil column) is established whereby the flow or outflow, water content, and pressure head are measured or inferred.

Basically, there are three options with respect to measurements made on the flow system: (1) the water content and pressure head distribution may both be measured, (2) the water content distribution may be measured and the pressure head inferred from water retention data, or (3) the pressure head distribution may be measured and the water content inferred from water retention data.

Table 6-2 shows the variety of approaches.

TABLE 6-2 SUMMARY OF LABORATORY INSTANTANEOUS PROFILE METHODS FOR HYDRAULIC CONDUCTIVITY

Reference:	Water Content From:	Pressure Head From:
Watson (1966)	Gamma attenuation	Tensiometers (pressure transducers)
Wind (1966)	Inferred from $\sigma(h)$	(1) Tensiometers (2) Nylon resistance elements
Vachaud (1967)	Gamma attenuation	Inferred from $h(\sigma)$ function for wetting
Weeks and Richards (1967)	Inferred from $\sigma(h)$	Tensiometers (mercury-water)
Flocker et al. (1968)	Gamma attenuation	Tensiometers (mercury-water)
Cassel et al. (1968)	Gamma attenuation	---
Vauchaud and Thorny (1971)	Gamma attenuation	Tensiometers (pressure transducers)
Rogers and Klute (1971)	Gamma attenuation	Tensiometers (pressure transducers)
Gillham et al. (1976)	Gamma attenuation	Tensiometers (pressure transducers)
Gillham et al. (1979)	Gamma attenuation	Tensiometers (pressure transducers)

Parameters measured-- Unsaturated hydraulic conductivity (cm sec^{-1}).

Method-- (Watson, 1966).

Apparatus: (1) Gamma attenuation system: (A) Cs ^{137} source, (B) NaI thallium-activated detector and conventional amplifier, (C) Pulse height analyzer, (D) Scaler equipment, and (E) Output recorder. (2) Tensiometry connected through a hydraulic selector switch to a pressure transducer. The output of the transducer is read with a digital voltmeter and recorded on a paper tape printer. (3) A porous PVC barrier through which water could be added or removed from the column and measure flow water connected to the column through the porous barrier. This is shown in Figure 6.14.

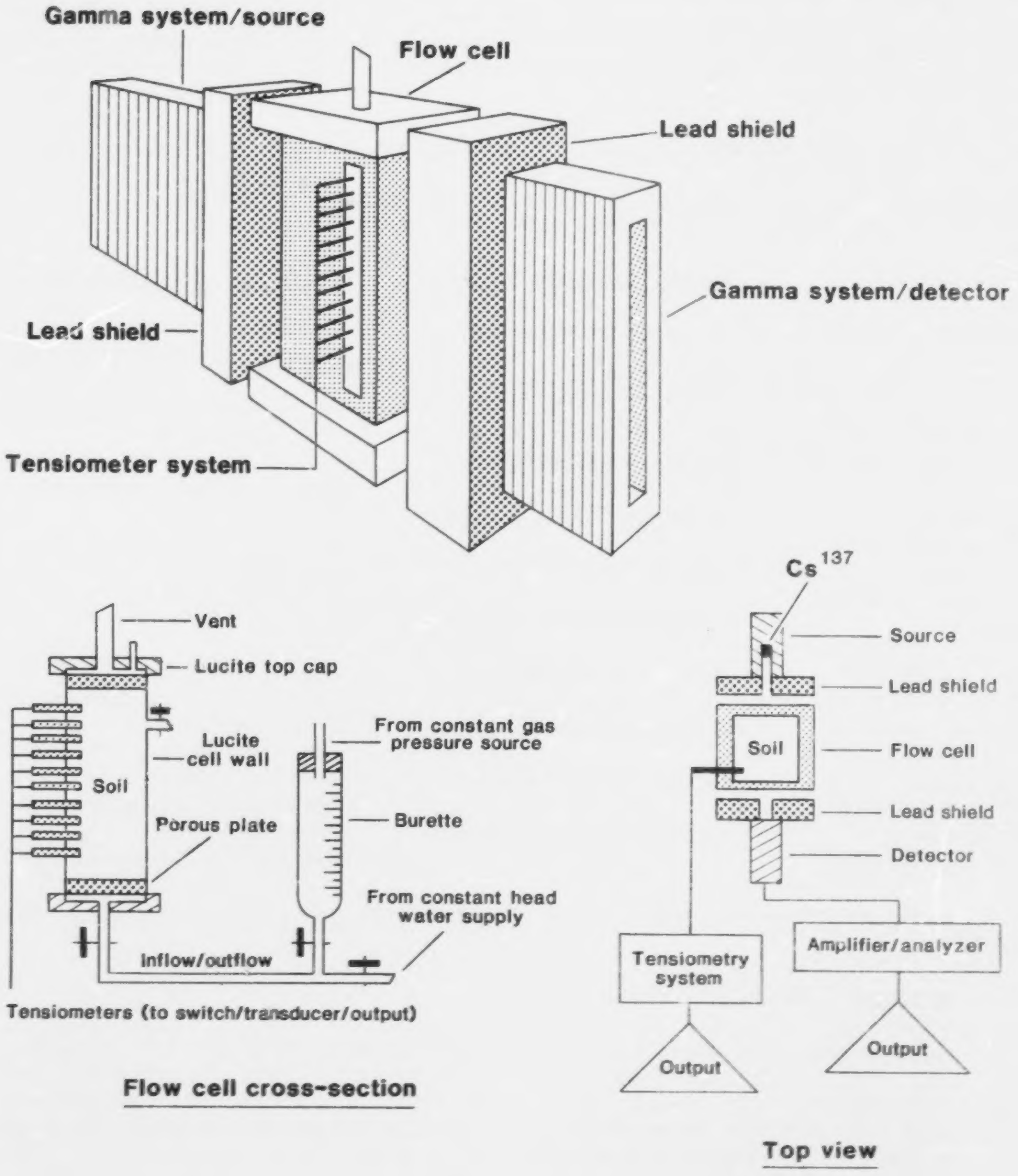


Figure 6.14 Diagram of flow cell, tensiometer, and gamma system. (Gillham et al., 1976).

Procedure:

(1) A steady-state condition is achieved at the start of the experiment by supplying excess water (distilled and boiled) to the surface of the column such that a very small head of water (1 mm) is maintained there.

(2) After the column is saturated and the water supply stopped, the drainage experiment commences with the disappearance of ponded water through the upper soil surface.

(3) Water content and water suction values over short time periods are recorded at different depths throughout the experiment.

(4) After the experiment is terminated, plot (a) soil water suction (cm) versus time on the abscissa for the various depths of measurements. Examples of these graphs are presented in Figure 6.15 and Figure 6.16.

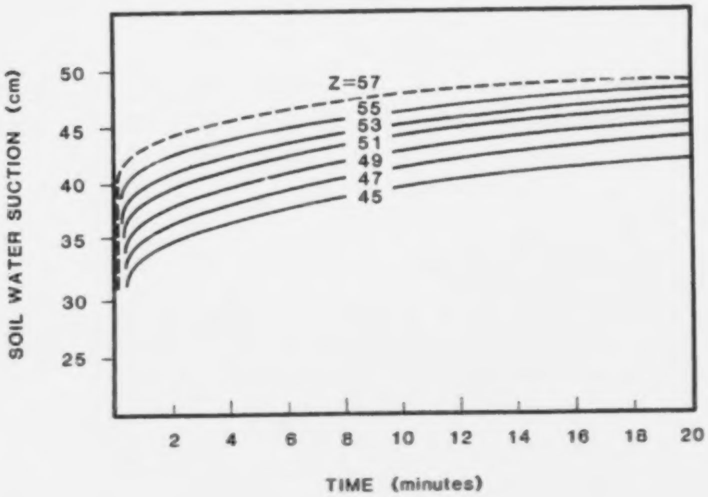


Figure 6.15 Variation of soil water suction with time at several column elevations (Watson, 1966).

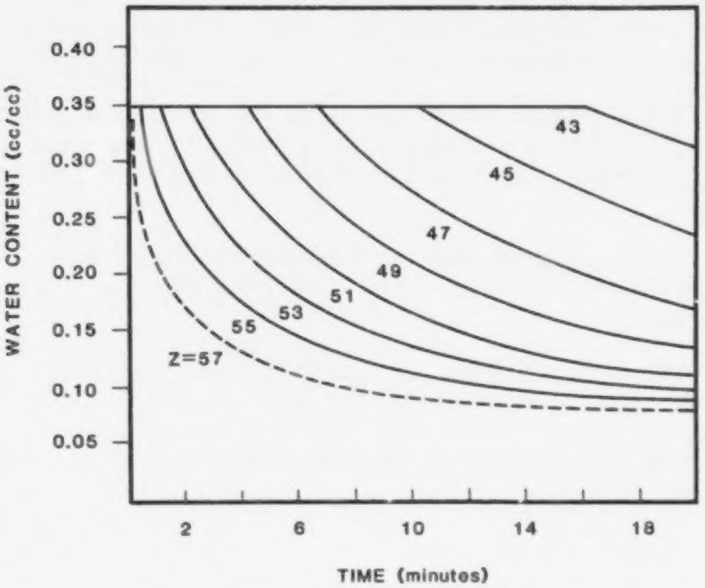


Figure 6.16 Variation of moisture content with time at several column elevations (Watson, 1966).

(5) Using the information in Figure 6.16 for the variations of water content with time for several column elevations, it is a straight foward matter to find the relation between $\partial w/\partial t$ and z at several required times through the use of the equation:

$$(\partial w/\partial t) = -(\partial v/\partial z)_t$$

where v = flow velocity (cm sec^{-1})
w = volumetric water content (cm^3 cm^{-1})
z = elevation above the datum plane defined as positive in the upward direction

The velocity profiles are obtained by integrating the $\partial w/\partial t$ profile curves graphically with respect to z. Examples of the resulting velocity profiles are shown in Figure 6.17 for times of 1, 3, 5, 10, and 20 minutes. Such profiles represent the instantaneous velocities down the column at the times stated.

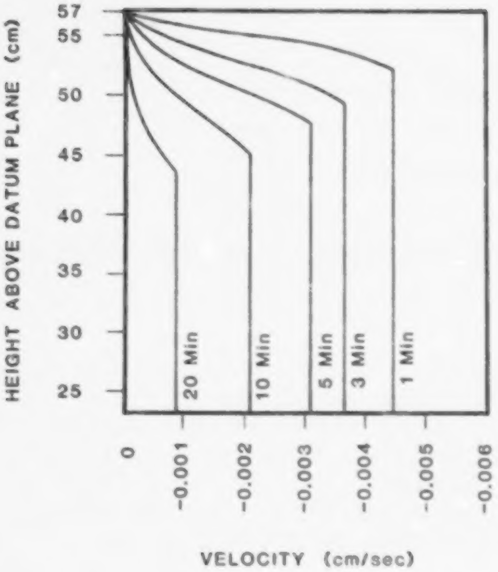


Figure 6.17 Instantaneous velocity profiles (Watson, 1966),

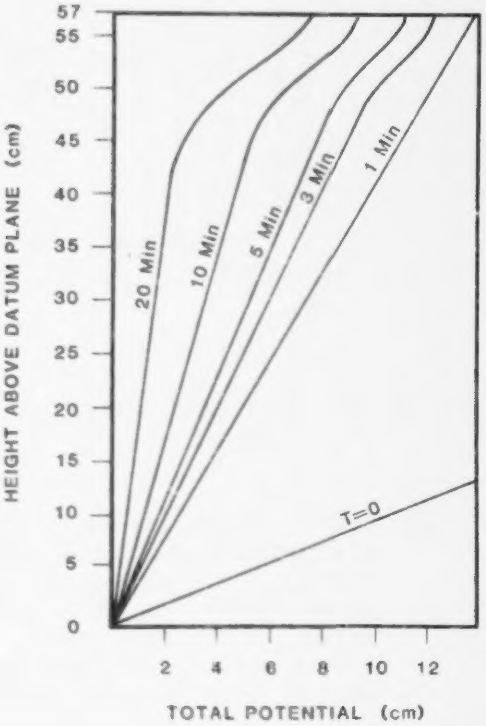


Figure 6.18 Instantaneous total potential profiles (Watson, 1966).

(It should be noted that the velocity is zero at the surface and rises to a maximum value at the drainage front, which is defined as the plane separating the partly drained upper profile and the still-saturated lower profile. The velocity is constant throughout the still-saturated zone of the column).

(6) Determine the soil water suction profile values at 1, 3, 5, 10, and 20 minutes from Figure 6.15. Because the total pressure head is equal to the negative suction component and the gravitational component, the total pressure head profiles at the above times may be readily plotted and are presented in Figure 6.18.

(7) The curves in figure 6.18 may then be differentiated graphically to give the positive potential gradient as shown in Figure 6.19.

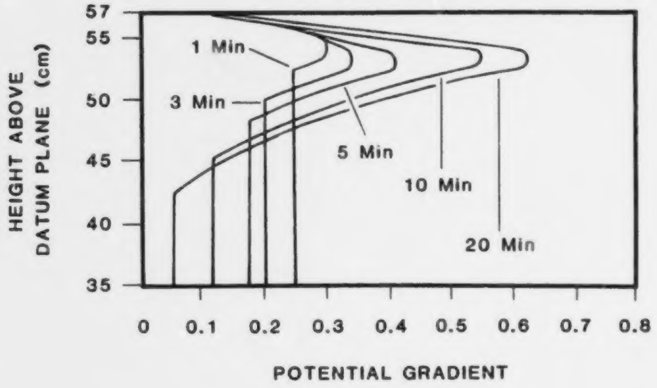


Figure 6.19 Instantaneous potential gradient profiles. (Watson, 1966).

(8) The instantaneous hydraulic conductivity for any elevation and time can be determined from Figures 6.17 and 6.19 by dividing the velocity value at that point in space/time by the corresponding potential gradient value, with due note being taken of the signs. Then the curve relating hydraulic conductivity can be plotted versus the water content as shown in Figure 6.20.

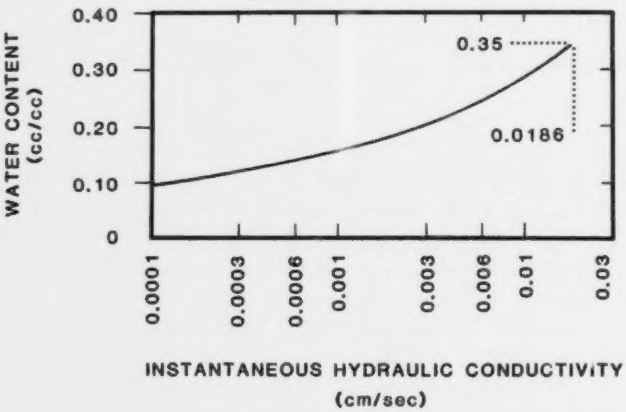


Figure 6.20 Water content-instantaneous hydraulic conductivity relation showing the computed value (Watson, 1966).

Precision and accuracy-- A comparison between measured and computed water content and pressure head values, including effects of hysteresis, has been provided by Gillham et al. (1979) for variations in the laboratory instantaneous profile method. This is shown in Table 6-3.

TABLE 6-3 COMPARISON OF MEASURED AND COMPUTED WATER CONTENT AND PRESSURE HEAD VALUES (Gillham et al., 1979)

	Average difference between measured and computed results	
	Pressure head h(cm)	Water Content (θ)
Slow drainage-rewet[1]		
Hysteretic-nonuniform	0.72	6.5×10^{1}
Nonhysteretic-nonuniform	0.72	2.2×10^{2}
Hysteretic-uniform	1.80	1.7×10^{2}
Rapid drainage-rewet[2]		
Hysteretic-nonuniform	1.00	1.2×10^{2}

[1] Calculated using data at t = 45, 68, 90, and 125 minutes
[2] Calculated using data at t = 11, 22, 45, and 68 minutes

Limitations of test-- (1) The time required to obtain data for the calculation of the water content versus hydraulic conductivity curve is a function of the pore size of the porous material and will increase with decreasing pore size; (2) Small sample size; and (3) Results are limited to tensiometer range of measurement.

Status of the method-- Main laboratory method for unsaturated hydraulic conductivity in agricultural sciences.

Thermocouple Psychrometers--

General description-- The thermocouple psychrometer technique is a method very similar to the instantaneous profile method except thermocouple psychrometers are used instead of tensiometers. Psychrometers measure the relative humidity of the pore air which can be translated into soil suction. In the testing procedure a soil sample is compacted into a plastic tube into which the calibrated psychrometers are positioned and sealed. Flow is initiated and measurements recorded. A moisture retention curve for the sample soil must also be determined.

Parameters measured-- Unsaturated hydraulic conductivity (cm sec^{-1}).

Method-- (Hamilton et al., 1981).

Apparatus: The basic equipment involved is: (1) plastic tube; (2) thermocouple psychrometers; (3) psychrometer instrumentation which includes: (a) a microvolt meter, (b) a strip-chart recorder, (c) a source of electric current for cooling the measuring junction, and (d) a switchbox when more than one psychrometer is used; (4) hypodermic syringes; (5) controlled humidity and temperature vessel; and (6) a water supply as shown in Figure 6.21.

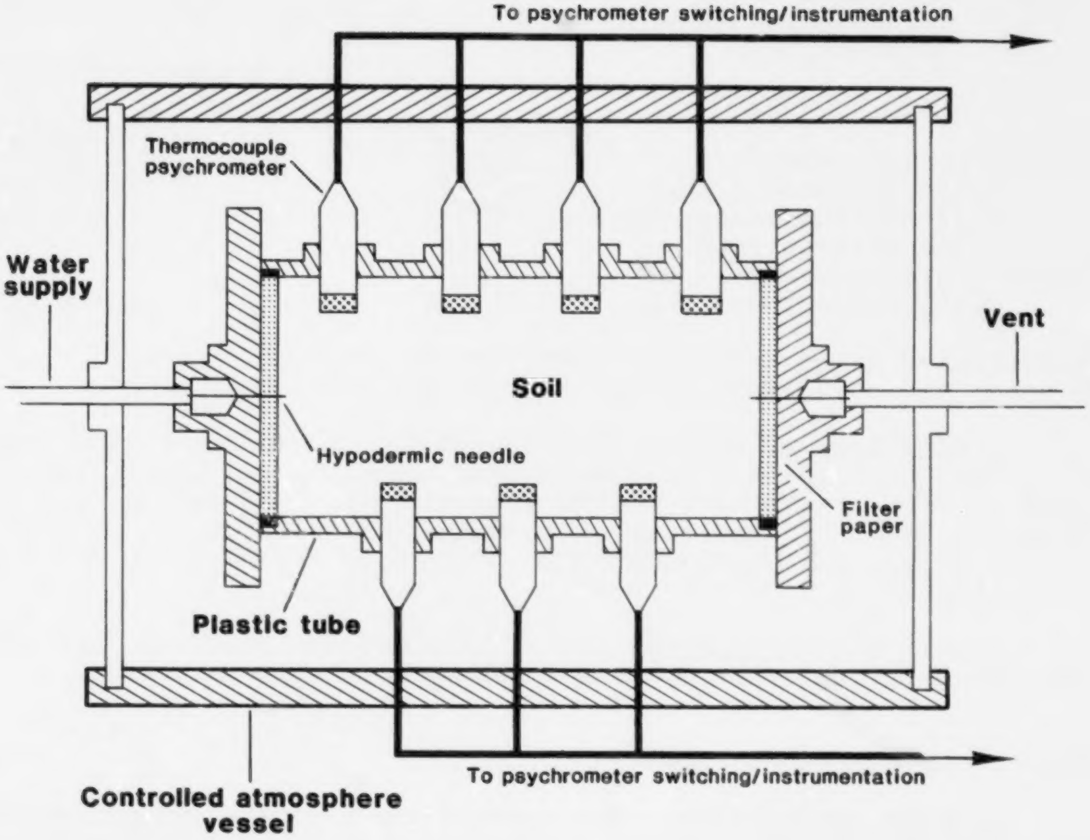

To psychrometer switching/instrumentation
Thermocouple psychrometer
Water supply
Vent
Soil
Hypodermic needle
Filter paper
Plastic tube
Controlled atmosphere vessel
To psychrometer switching/instrumentation

Figure 6.21 Cross-section of thermocouple psychrometer permeameter.

Procedure:

(1) The sample soil is sieved through a No. 40 sieve and then water is added to obtain a gravimetric water content of 5.0%.

(2) Samples are then compacted into a plastic tube with an inside diameter of 50 mm and length of 114 mm at a density of 107 pcf.

(3) Psychrometers are inserted and sealed in seven ports along the tube that are spread at a distance of 13 mm.

(4) The ends are closed using plastic end plates with O-ring seals.

(5) The outflow end is provided with a hypodermic needle to act as an air vent and a sheet of filter paper to help maintain a uniform head.

(6) The inflow end is provided with a 5 cc capacity hypodermic syringe for inflowing water and several discs of filter paper are used to help distribute the flow across the entrance face. The plunger of the syringe is pushed at a controlled rate using a standard mechanical loading press (screw jack driven by electric motor through a variable speed gear box).

(7) The entire cell is then placed into a vessel of high humidity and controlled temperature.

(8) Flow is then initiated (typical rates of 0.7 cc/day) with psychrometer readings taken every 24 hours.

(9) Flow is continued until the suction at the inflow has decreased to about 4 atmospheres, and the leading edge of the wetting front has at least reached the farthest psychrometer.

(10) Inflow is then stopped and the psychrometers are removed with a water content sample taken from the soil around each psychrometer hole.

(11) The sample is then extruded and cut into discs to obtain another measurement of water content.

(12) Such values of volumetric water content (θ) are evaluated from the suction measurements and from the moisture retention curve (water content versus suction), which are either measured on a duplicate sample or are obtained from measurements of water content taken at the beginning and end of a test and matched to the measured suctions.

(13) Then plots of suction versus horizontal position are prepared with values of the hydraulic conductivity gradient (dp/dx) computed for each probe and each time where p is defined as the negative of the pore water pressure.

(14) Volumetric water content is then plotted versus horizontal position with the total volume of water downstream of each point determined for each time by integration:

$$V_w = \int \theta A \, dx$$

where

V_w = total volume of water downstream of each point
θ = volumetric water content
A = total cross-sectional area of sample
x = position coordinate

(15) Then the rate of flow past a point (dV_w/dt) is computed for each probe location and each time.

(16) Hydraulic conductivity is computed from the equation:

$$K = \frac{V_w}{A} \frac{dV_w/dt}{dp/dx}$$

where k = hydraulic conductivity
V_w = unit weight of water
A = total cross-sectional area of sample
dV_w/dt = rate of flow past each point
dp/dx = hydraulic gradient

(17) From calculations of hydaulic conductivity, plots may be developed of K versus suction, water content, or degree of saturation.

Precision and accuracy-- The precision and accuracy of this method hinges on obtaining an accurate water content-versus-suction relationship and accuracy of suction measurements during the hydraulic conductivity test. The accuracy of the moisture curve is variable due to the hysteresis phenomena which makes the wetting (absorption) moisture retention curve different than the drying (desorption) moisture retention curve. The accuracy of suction measurements by psychrometers for the range of 1 to 75 atmospheres has been suggested by Daniel (1979) to be between 5 and 30% provided there are no extreme fluctuations in temperature, corrosion problems, or any gross blunders during calibration of the psychrometers or during the actual test procedure.

Limitations of test-- (1) Small sample may be unrepresentative of field conditions; (2) Applicable to suctions between 1 and 80 atmospheres which translates to clays with degrees of saturation between approximately 30 and 90 percent, and sands with degrees of saturation less than 50 percent (Daniel et al., 1981) (3) Susceptibility of psychrometer corrosion in acidic soils; (4) Cannot be used to measure unsaturated hydraulic conductivity near saturation (less than 1 atm); (5) Requires roughly three weeks per test not including calibration of the psychrometers or determination of the moisture retention curve.

Status of the method-- The thermocouple psychrometer method for measurement of unsaturated hydraulic conductivity is a recently developed testing procedure that is meant to be applied to compacted, relatively dry arid soils where suctions exist that cannot be measured by tensiometers or pressure plate apparati.

6.2.2 Field Tests

Crust Test--

General description-- The crust technique is a field adaptation of the laboratory procedure for flow through an impeding layer. The crust test can be used to determine both saturated and unsaturated conductivity.

The crust test method requires carving out a cylindrical pedestal of soil, whose upper surface is at the depth where the hydraulic conductivity rate is desired. A ring infiltrometer of the same diameter as the pedestal is firmly affixed to the top of the pedestal so that the soil's horizontal surface is enclosed by the ring. A paste consisting of gypsum and sand, mixed with a small amount of water, is spread over the entire horizontal surface and is allowed to harden, forming a crust. When water is introduced through the infiltrometer and maintained at a constant head, flow into the soil is restricted by the crust. A constant, steady state flow rate is established, inducing a nearly uniform moisture potential (measured by tensiometers) and the steady state flow rate (measured at the infiltrometer with a burette) defines a plot of infiltration versus soil moisture tension (the K(h) curve). Crusts of different resistances yield different points on the K(h) curve. A series of crusts ranging from greater to lower resistance assures that the data points fall on the wetting curve.

The technique can be extended to include measurement of saturated hydraulic conductivity which requires the addition of a barrier to flow around the sides of the soil pedestal. This is usually done with the soil pedestal thoroughly wetted and with a slurry of dental grade plaster applied to the sides. No crust is applied to the surface in this case.

Parameters measured-- Saturated and unsaturated hydraulic conductivity (cm sec^{-1}).

Method-- (SSWMP, 1978).

Apparatus: The basic equipment required and the experimental set-up for the crust test are shown in Figure 6.22. The items required are: (1) Ring infiltrometer (24 cm diameter); (2) Tensiometers; (3) Constant water supply; and (4) Crust made from gypsum, sand and water.

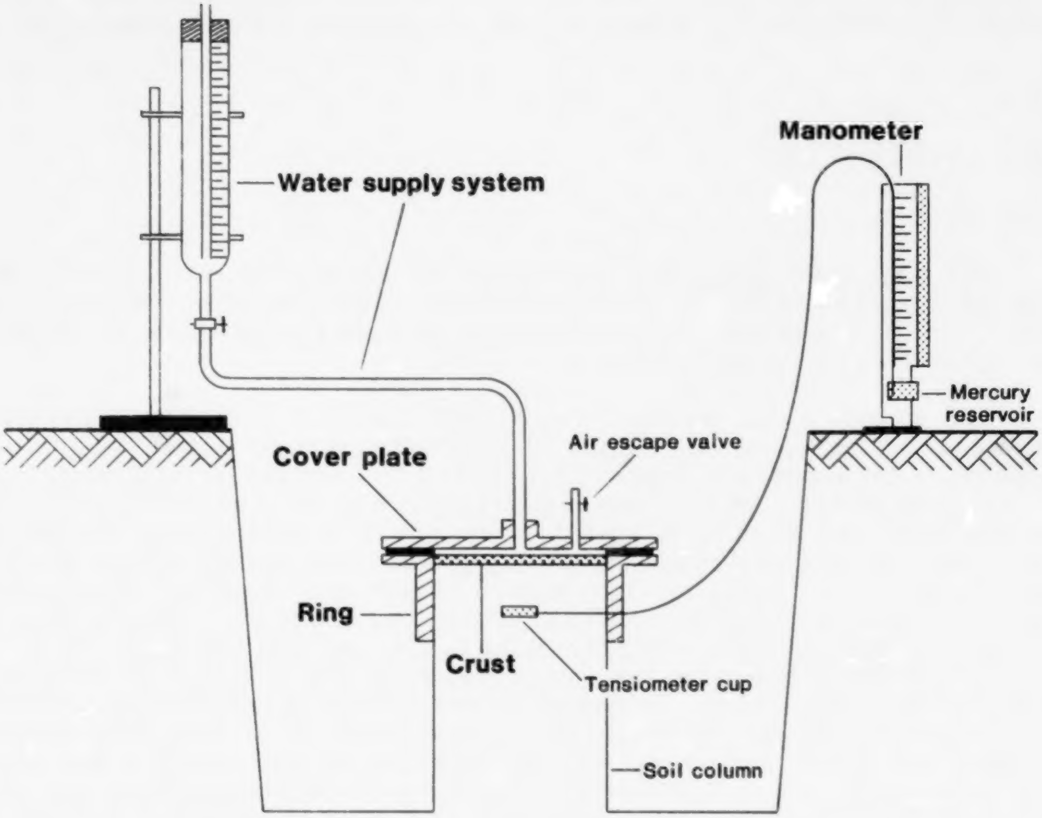


Figure 6.22 Schematic of the crust test apparatus. (SSWMP, 1978).

Procedure:

(1) A hole is dug to a level just above the horizon of interest.

(2) A free-standing soil pedestal is carved down several centimeters to facilitate placement of the ring infiltrometer on the pedestal. It should be noted that, at first, the pedestal is made four or five centimeters larger than the ring.

(3) The infiltrometer is then placed on the top of the pedestal and carefully pushed into the soil with excess soil around the outside of the ring cut away with a knife. The ring is pushed down until about 1.5 cm of side wall remains above the soil.

(4) The soil pedestal must be carved to a height of at least one ring diameter. With a 24 cm ring, a height of 30 cm is recommended.

(5) After the pedestal is formed, it is wrapped with aluminum foil to reduce evaporation from sidewalls.

(6) A horizontal hole is augered into the side of the pedestal at a depth of 2-5 cm under the infiltrative surface in the middle of the pedestal. The diameter of the hole should be slightly less than the diameter of the porous cup to assure a tight fit. After the tensiometer cup is in place, the hole should be sealed with mud or glue to prevent evaporation.

(7) The free end of the tensiometer runs through a manometer board to a mercury reservior. A graduated scale is used to read potential as centimeters of water when mercury rises on this scale. The difference in elevation between the porous cup and the surface of the mercury in the reservior is referred to as the correction factor or CF, which can be determined in the field with two meter sticks and a level. It is subtracted from the total tension to yield matric soil tension.

(8) Once in place, the tensiometer is filled with de-aired water using a 50-ml syringe with a 22-gauge needle.

(9) With the pedestal instrumented, a crust is made from the appropriate proportions of sand, gypsum, and water. A higher sand content in the mixture will produce a crust of less resistance and higher rates of flow. Generally, the first crust to be used will be the most resistant.

(10) After the crust has hardened, the gasket and cover plate of the ring infiltrometer are bolted into place so that the air escape position is at the highest elevation possible. The water supply system is activated and allowed to fill the chamber and, when all air is purged, the Mariotte tube and stopper are placed into the burette to reduce the hydraulic head, and the air escape port is capped. When air bubbles begin to rise from the tip of the Mariotte tube, the first volume measurement can begin.

(11) Volume measurements are recorded periodically until equilibrium is reached. Tension measurements are recorded simultaneously. The hydrauliuc conductivity at that tension is equal to the constant inflow rate.

(12) After equilibrium has been reached, the first crust is removed and replaced by a less resistant one and steps

10 and 11 are repeated. Each succeeding crust yields a point on the K curve. The results for the B_{22}t horizon of the Batavia silt loam are shown in Figure 6.23.

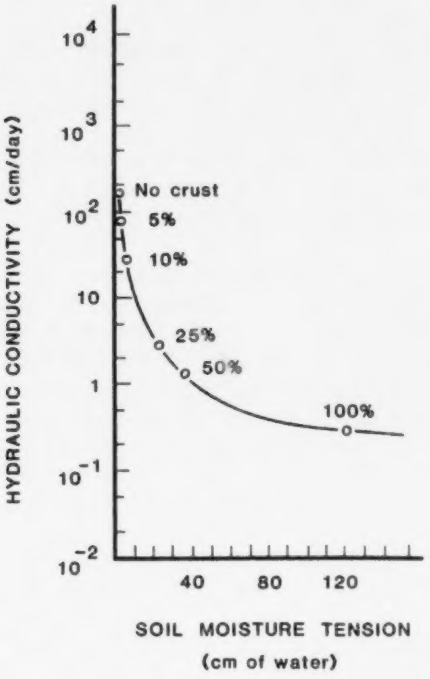


Figure 6.23 Hydraulic conductivity versus pressure head for B_{22}t horizon of Batavia silt loam (SSWMP, 1978).

Each point represents the tension-conductivity pair caused by a particular crust. The percentage indicated by each point is the gypsum-content of the crust that was used to obtain that point.

Precision and accuracy-- Baker (1977) compared pedestal height, pedestal diameter, and operator differences on two soils for the variation in hydraulic conductivity measurements. He reported that operator differences were small and coefficients of variation were lower for saturated hydraulic conductivity (1.2%) than unsaturated (12.0%).

Precision is good because of direct measurement of flux and pressure potential using transducers and Mariotte devices. Accuracy is good because of large sample size.

Limitations of test-- (1) Large time requirement is necessary to achieve steady state flow under crusts of high resistance; (2) It is difficult to assure that good contact between ring and pedestal is made; and (3) Results limited to range of tensiometer measurement.

Status of the method-- The method was first developed around 1970 (Hillel & Gardner, 1970). Since that time a great deal of research effort has been conducted by the Small Scale Waste Management Project at the University of Wisconsin (SSWMP, 1978) under the sponsership of EPA.

Instantaneous Profile--

General description-- The traditional instantaneous profile technique in situ is a method where a nearly level plot of soil is diked to pond 2-3 cm of water. After addition of water the plot is covered to prevent evaporation, and drainage occurs. At frequent intervals both pressure head and water content values are measured. From these measurements, instantaneous values of the pressure gradients and fluxes can be determined, which will also provide hydraulic conductivity values.

As with the laboratory instantaneous profile method, there have been various applications by several authors. These citations are listed in Table 6-4.

TABLE 6-4 LIST OF LITERATURE CITATIONS FOR FIELD INSTANTANEOUS PROFILE METHOD

Richards et al., 1957
Ogata and Richards, 1957
Nielson et al., 1962
Rose et al., 1965
Rose and Krishnam, 1967
Van Bavel et al., 1968
Davidson etal., 1969
Renger et al., 1970
Hillel et al., 1972
Roulier et al., 1972
Nielson et al., 1973
Baker et al., 1974
Cheng et al., 1975
Nagpal and DeVries, 1976
Carvallo et al., 1976
SSWMP, 1978
Simmons et al., 1979
Dane, 1980
Libardi et al., 1980

Parameters measured-- Unsaturated hydraulic conductivity (cm sec^{-1}); diffusivity (cm^2 sec^{-1}).

Method-- Traditional instantaneous profile (SSWMP, 1978).

Apparatus: Equipment required consists of a neutron probe to measure water content and tensiometers to measure pressure head. A diagram of this set-up is shown in Figure 6.24.

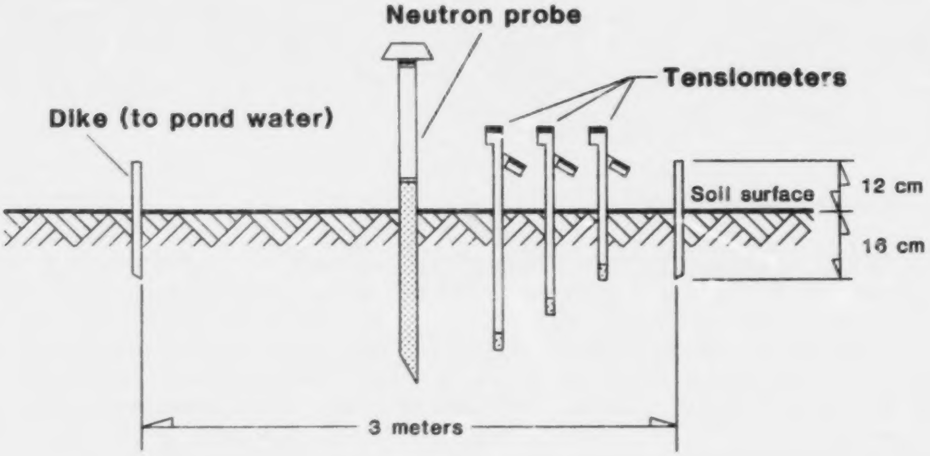


Figure 6.24 Field set-up for instantaneous profile method (SSWMP, 1978).

Procedure:

(1) Once the plot has been prepared and the instruments are in place, the plot should be wetted a day or two before the start of actual measurements.

(2) Water is then ponded on the surface until the tensiometers remain constant.

(3) As soon as the water is no longer visible on the surface, the plot is covered by plastic, and the first measurements are taken at time = zero.

(4) As the internal drainage process proceeds, periodic measurements are made of water content and hydraulic head throughout the profile. These readings must be taken frequently (every hour or two) but can be taken at greater time intervals (daily) as the internal drainage process slows down.

(5) Plot volumetric moisture content variation with time at each depth from neutron-meter data.

(6) Prepare a table with the following headings:

t	Z	$\frac{d\theta}{dt}$	$\frac{dZd\theta}{dt}$	$q = \sum d^2 \frac{d\theta}{dt}$
(days)	(cm)	(days^{-1})	(cm day^{-1})	(cm day^{-1})

It should be noted that $d\theta/dt$ are the slopes at particular points of time from the graph of step 5.

(7) Plot matric suction variation with time for each depth from tensiometric data.

(8) Prepare a table with the following headings:

Z	q	$\frac{dH}{dZ}$	K	θ
(cm)	(cm/day)	(cm/cm)	(cm/day)	(%)

K is calculated by dividing q by dH/dZ for each time. It should be noted that dH/dZ are the slopes for particular depths in the graph of step 7.

(9) Plot hydraulic conductivity against volumetric moisture content and draw best-fit curves for the different layers by use of semi-log paper (i.e., log K versus θ).

(10) Evaluate whether the entire profile can be characterized by a single curve or whether each depth has a separate $K(\theta)$ curve.

Method II-- Unit gradient-drainage.

In a uniformly draining soil profile, the hydraulic gradient is often unity, and the water content is a function of time and nearly independent of depth. This relation can be expressed as:

$$D = \frac{Ldh}{dt}$$

where D = diffusivity (cm^2 sec^{-1})
L = length (cm)
h = average hydraulic head (cm)

This method differs from the traditional instantaneous profile method in that instead of measuring both water content and pressure head in the field, only pressure head is measured in the field, and water content from laboratory-determined water retention curves is used to calculate hydraulic conductivity from the equation $K = D d\theta/dt$. Description of the unit gradient-drainage has been reported by: Black et al., 1969; Davidson et al., 1969; Gardner, 1970; Klute, 1972; Nielson et al., 1973; and Simmons et al., 1979.

Method III-- Libardi method (Libardi et al., 1980).

The Libardi method is a recent attempt to simplify the field determination of hydraulic conductivity by means of a modified instantaneous profile method. Similar to the unit-gradient drainage method, it measures only one parameter rather than both water content and pressure head. However, unlike the unit-gradient drainage method, the other parameter is not measured in the laboratory. In fact, in the Libardi method, only the neutron probe device is used for water content measurement, and hydraulic conductivity is determined without any further information.

Precision and accuracy-- Dane (1980) compared the Libardi method to the traditional instantaneous profile method and found good agreement subject to a modification of the Libardi method at higher values of water content. The results are shown in Figure 6.25.

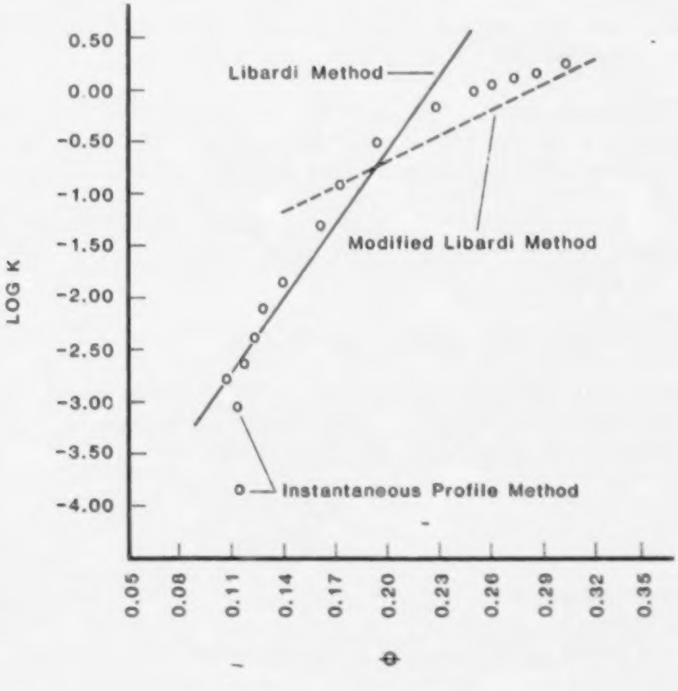


Figure 6.25 Comparison of traditional instantaneous profile method to Libardi method (Dane, 1980).

Precision is only fair to good on fine-textured soils where water movement is slower. The instantaneous profile method is probably one of the most accurate methods because of large sample size.

Limitations of test-- (1) Values of matric suction measured are limited to tensiometer range of less than about 0.9 atm (Olson and Daniel, 1981); (2) Field plot must be level; (3) It is not applicable to cases where lateral flow is appreciable (Hillel et al., 1972); (4) Plots (3 m x 3 m) may not be large enough to assure one-dimensional vertical flow at the center of plot if surrounding area is vegetated and strongly evapotranspiring (Baker et al., 1974); and (5) May take weeks to perform test on soils with low hydraulic conductivities or restricting layers.

Status of the method-- Has been regularly used in the agricultural sciences as it is the most accurate method for prediction of field behavior. Several variations of the method exist, including more recent attempts to streamline the procedure and time requirements.

6.2.3 Calculation Methods

Because of various difficulties involved in the direct measurement of the hydraulic conductivity function, there has been considerable interest in the potential of calculating the conductivity from other properties of the medium that may be easier to measure such as pore size distribution or the water retention curve. The basic concepts are given by Childs and Collis-George (1950), Marshall (1958), and Millington-Quirk (1960, 1961, 1964). Because there is quite a variety in the approaches, brief summaries are provided for a number of research efforts.

Nielson et al. (1960) compared the conductivity calculated by the Childs Collis-George and Marshall methods with measured conductivity values on four soils in the pressure-head range 0 to -100 cm of water. The Childs Collis-George method gave the best results, in part due to the matching factor used, while the Marshall method gave results that were too high.

Jackson et al. (1965) used a matching factor with the Millington and Quirk method, calculating conductivity from both the drying and wetting curves to examine the effect of hysteresis. Results showed that hydraulic conductivity relations for both curves were similar.

Laliberte and Corey (1967) presented an equation for calculating the hydraulic conductivity of unsaturated materials which utilized an empirical functional relationship between relative hydraulic conductivity, K, and the capillary pressure, P.

Kunze et al. (1968) also used a matching factor with a modified Millington and Quirk method.

Brust et al. (1968) used the Millington-Quirk method with a matching factor, and the Laliberte-Brooks-Corey method to calculate the hydraulic conductivity water content function for several horizons of a clay loam soil with laboratory determined water retention curves. The calculated hydraulic conductivity relations obtained by the Millington-Quirk and Laliberte-Brooks-Corey methods were compared to field conductivity by the instantaneous profile method.

Green and Corey (1971) developed a computational method based on the pore-interaction model of Marshall which seemed to offer no particular advantage over either the Marshall equation with matching factor or the Millington-Quirk equation with matching factor. From their results, they concluded that such methods appeared sufficiently reliable for field applications.

Bruce (1972) compared the hydraulic conductivity from laboratory outflow data to procedures for calculating hydraulic conductivity from Childs Collis-George (1950), Marshall (1958), Millington-Quirk (1961), and Laliberte et al. (1966). He concluded that all methods for describing the transport system can be used with discrimination to calculate the hydraulic conductivity of many soil materials with adequate accuracy.

Roulier et al. (1972) compared field-measured hydraulic conductivity by the instantaneous profile method to three different laboratory methods: (1) conductivity by the laboratory instantaneous profile method, (2) calculated hydraulic conductivity by the Marshall equation from laboratory moisture curves on intact cores and from field data, and (3) calculated conductivity by the Millington-Quirk method from laboratory and field moisture curves. They concluded that the laboratory instantaneous profile method, the Marshall equation method, and the Millington-Quirk method were qualitatively similar because all methods require the use of a matching factor to simulate field hydraulic conductivity. However, without such matching factors, the laboratory or calculated hydraulic conductivity was found to range from 2 to 20 times the hydraulic conductivity determined in the field. They also recommended that the hydraulic conductivity value used to calculate the matching factor for these three methods be measured in the field within the soil-water content range under question.

One of the many objectives of Nielson et al. (1973) was to evaluate the suitability of various soil-water equations for predicting hydraulic conductivity under field conditions. Using the calculation techniques of Childs and Collis-George (1950), Marshall and Millington-Quirk (1960, 1961, 1964), and Kunze et al. (1968), they concluded that the accuracy of the calculated hydraulic conductivity was strongly related to the accuracy of the matching factor.

Campbell (1974) proposed a modified Childs and Collis-George method which was compared to measured hydraulic conductivity as well as to coventionally-calculated hydraulic conductivity by the Millington-Quirk method. Agreement between the three methods was good for the Botany sand, the Guelph loam, and the A_p horizon of the Cecil sandy loam. Agreement was not good for the B_2 and B_3 horizons of the Cecil sandy loam.

Carvallo et al. (1976) compared the measured hydraulic conductivity from the unit-gradient drainage field method to the calculated hydraulic conductivity by a modified Green and Corey method. They concluded that agreement of the calculated K values and in situ K values was best when the matching factor was selected at the lowest water content for which in situ K was measured.

Simmons et al. (1979), in a broad study of spatial variability of field-measured soil-water properties, included the calculation of hydraulic conductivity by the Millington-Quirk method. They concluded that the error in the Millington-Quirk method of estimating hydraulic conductivity on the sample soil was dependent on the matching factor K_s/K_{sc} (where K_s = actual hydraulic conductivity at saturation, and K_{sc} = calculated hydraulic conductivity at saturation), and the errors in two scaling factors, K_m and α.

Libardi et al. (1980) proposed two new methods of estimating hydraulic conductivity that are called the Water Content Method and the Flux Method, which are compared to a third method developed by Chong et al. (1979), and measured K values. Their results suggest that all three methods provide comparable estimates of hydraulic conductivity and can be applicable to situations where soil horizons do not differ dramatically in hydraulic conductivity. They also believe that a better characterization of hydraulic conductivity can be achieved by using simple methods at a greater number of sites than more rigorous methods at just a few sites.

Dane (1980) compared four methods for determining hydraulic conductivity: (1) traditional field determination by the instantaneous profile method, (2) the Van Genuchten (1979) analytical model using laboratory water retention curves, (3) the Van Genuchten analytical model using field-dervied water retention curves, and (4) a modified field instantaneous profile method for fine-textured soils developed by Libardi et al. (1980). The results of this analysis showed good agreement among all four methods.

Integration of this information illuminates several points: (1) Most of the soils used in these experiments have been coarse-textured with relatively high hydraulic conductivities (usually 10^{-4} cm sec^{-1} or greater); (2) Roulier et al. (1972), Carvallo et al. (1976), and Simmons et al. (1979) support the recommendation that the K selected in determining the matching factor should be measured in the field (rather than the laboratory) within the suction range being studied, (3) Recent work of Dane (1980) and Libardi (1980) show great potential for providing simplified methods for hydraulic conductivity determination, and (4) Calculations of unsaturated hydraulic conductivity can be used to estimate saturated hydraulic conductivity. In fact, matching factors of K actual/K calculated are most often determined at or near saturation.

6.2.4 Diffusivity

Pressure Outflow--

General description-- In the pressure outflow method, the time dependence of the outflow of water from a soil core on a porous plate or membrane in a pressure cell is used to determine the soil-water diffusivity (D).

Hydraulic equilibrium is first established in a layer of soil (usually 1-5 cm in depth), with the gas phase pressure in the cell at a given level. Beginning at or near saturation, step increases of gas pressure are applied to produce an outflow of water, and the volume of outflow as a function of time is measured. Paired values of diffusivity and water content are obtained from each pressure increment and thus the drainage function, $D(\theta)$, can be plotted. Because the total volume of outflow and the pressure head increment corresponding to each gas phase pressure increment are known, the water capacity (C) can be obtained and used to calculate hydraulic conductivity from the relationship:

$$K = DC$$

where K = unsaturated hydraulic conductivity (cm sec-1)
D = diffusivity (cm^2 sec^{-1})
C = water capacity (cm^{-1}).

Parameters measured-- Diffusivity (cm^2 sec^{-1}).

Method-- (Klute, 1965c).

Apparatus: The essential components of this laboratory set-up are shown in Figure 6.26. The components are: (1) pressure chamber with a porous plate or membrane; (2) an outflow-volume-measurement system; (3) a system for control of the gas-phase pressure in the chamber; (4) a system for removal of gas bubbles from beneath the porous plate or membrane; and (5) a timing device.

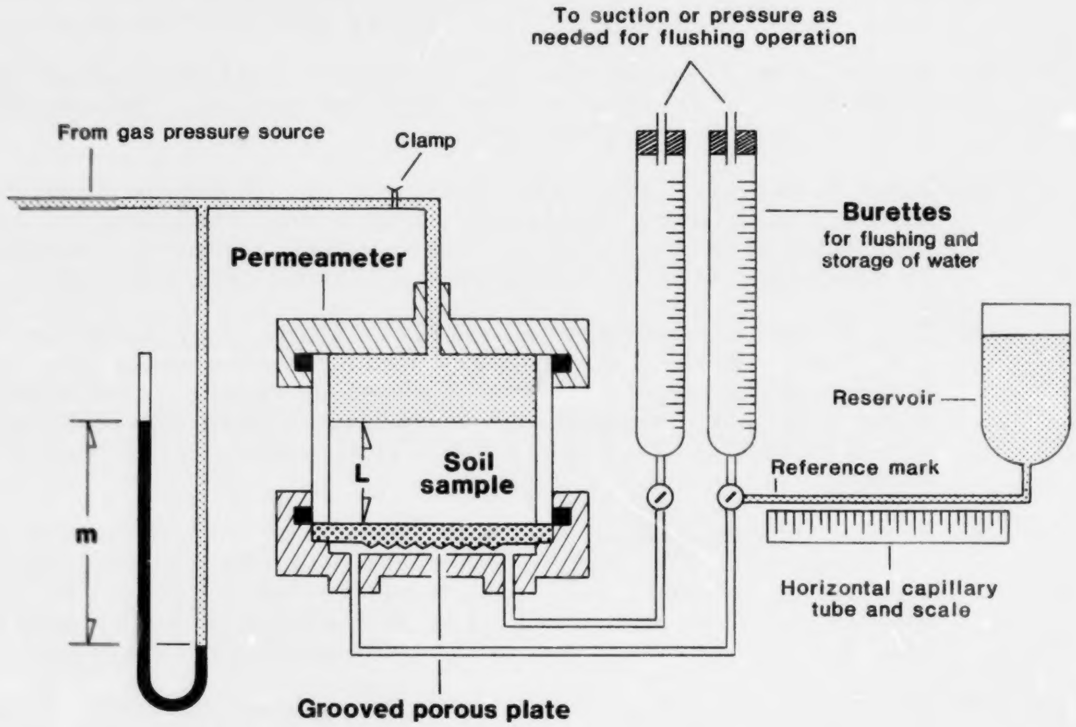

To suction or pressure as needed for flushing operation
From gas pressure source
Clamp
Burettes
for flushing and storage of water
Permeameter
Reservoir
Soil sample
L
m
Reference mark
Horizontal capillary tube and scale
Grooved porous plate

Figure 6.26 Diagram of apparatus for the outflow method of soil water diffusivity determination (Klute, 1965c).

Procedure:

(1) Saturate the porous plate by wetting it under vacuum or soaking it for a long time in de-aired water.

(2) Assemble the lower end-cap and the set-up for measuring the volume of outflow. Remove all air bubbles from the ouflow system.

(3) Place the sample upon the porous plate, and assemble the cell. Saturate the sample by soaking it in water.

(4) After saturation, close the cell and apply the lowest gas-phase pressure desired. When outflow equilibrium

has been reached, carry out the flushing operation to remove any air from beneath the plate and check again for equilibrium. Equilibrium is indicated when the meniscus in the horizontal tube does not move.

(5) Adjust the position of the meniscus in the horizontal tube to the starting mark. Record the burette readings.

(6) Close the clamp on the air pressure line and raise the pressure in the line by the desired amount. Record the initial and final pressures.

(7) Simultaneously, open the clamp on the pressure line and start the timing device. Record the position of the meniscus as a function of time. Take frequent readings in the beginning of outflow and fewer toward the end.

(8) Continue to record the outflow until equilibrium is attained. Make the necessary measurements to obtain the total volume of water $Q(\infty)$ removed from the sample as a result of the increase in pressure. Flush any gas from beneath the plate before the final volume readings are taken.

(9) Repeat steps 4-8 at as many levels of gas pressure as are desired. The number of steps will be determined by the range of soil water content to be covered, by the amount of time available for the measurements, and by the desired delineation of the diffusivity function.

(10) Determine by gravimetric means the water content of the entire sample after the last equilibrium has been attained.

(11) Construct a plot of the quanitities log $(1-Q(t)/Q(\infty))$ versus log $(Dt/4L^2)$ from the following equation:

$$1 - \frac{Q(t)}{Q(\infty)} = \frac{8}{\pi^2} \sum_{m=0}^{\infty} \frac{1}{(2m+1)^2} \exp \left[\frac{-(2m+1)^2 \pi^2 Dt}{4L^2} \right]$$

where

$Q(t)$ = volume of outflow at time t
$Q(\infty)$ = total volume of outflow from applied pressure increment
m = initial cell pressure

The plot will be referred to as the overlay or theoretical curve. The data for the construction of the overlay is presented in Table 6-5.

TABLE 6-5 REDUCED DIFFUSIVITY Dt/L^2 VERSUS $1-Q(t)/Q(\infty)$ FOR CONSTRUCTION OF THE OVERLAY (Klute, 1965c)

Dt/L^2	$1-Q(t)/Q(\infty)$	Dt/L^2	$1-Q(t)/Q(\infty)$
0.000	1.0000	0.040	0.7743
0.001	0.9643	0.070	0.7014
0.002	0.9495	0.100	0.6433
0.004	0.9286	0.200	0.4959
0.007	0.9056	0.400	0.3022
0.010	0.8872	0.700	0.1390
0.020	0.8404	1.000	0.0690
		1.4185	0.0245

(12) From the experimentally determined volume-outflow data, calculate the quantity $1-Q(t)/Q(\infty)$. If it was possible to hold all the outflow due to a given pressure increment in the horizontal tube, use the scale readings for the position of the meniscus to calculate the outflow ratio. Absolute values of volume are not needed because the units of quantity cancel. (However, it will be necessary to use the cross-sectional areas of the tube when calculations of the water content of the sample are to be made.)

(13) On another sheet of the same lot of log/log graph paper used for the overlay, construct a plot of log $1-Q(t)/Q(\infty)$ versus log t, using the experimental data.

(14) Place the theoretical curve over the experimental curve, match the log $1-Q(t)/Q(\infty)$ scales, and, by translation along the log $(Dt/4L^2)$ axis only, bring the theoretical and experimental curves into coincidence.

(15) Select any convenient value of $Dt/4L^2$ from the overlay and read the corresponding value of t from the experimental curve. If the chosen value of $Dt/4L^2$ is represented as w, then the diffusivity is given $D = w4L^2/t$ where t is the experimental value of time corresponding to the chosen value of w.

(16) The water content - pressure head curve can be calculated from the final water content of the sample and from the outflow volumes corresponding to each pressure increment. If the volume of the sample is V, the specific water capacity C is given by $C = Q(\infty)/V\Delta h$.

(17) The hydraulic conductivity is calculated by $K = DC$.

Precision and accuracy-- Many authors, including Olson and Daniel (1981), have criticisms relating to the assumption that a value of the hydraulic conductivity is constant over the small increments of gas pressure and conclude that the difficulty in the interpretation of the data and lack of replicated results present serious application difficulties. On the other hand, Klute (1972) maintains that a number of investigators have obtained hydraulic conductivity values, at least to within half an order of magnitude.

Limitations of test-- (1) As mentioned above, there remain both experimental and theoretical difficulties in the method affecting accuracy and precision of results. (2) Again, the limitations of laboratory tests for predicting field conditions are often particularly applicable to this method where soil core length is usually 1-5 cm (more often nearer the 1 cm end). (3) The test has many variations beyond the short column-small increment method described. Either disturbed or undisturbed cores have been used. Inflow rather than outflow has been measured; suction has been applied to the bottom rather than pressure to the top; one large pressure increment rather than several small ones has been used; as have tests for pressures under 1 atmosphere compared to tests for pressures from 1-15 atmospheres.

Status of method-- This method has been widely used in the agricultural sciences for difficulties associated with soil-water problems other than hydraulic conductivity. A pressure membrane apparatus for pressures between 1 and 15 atmospheres has been accepted by the American Society of Testing Materials as Standard D 3152-72.

Hot Air Method--

General description-- In this quick method, an undisturbed small column of soil in a cylinder (diameter 5 cm, height 10 cm) is saturated with water by capillary action. Then hot air (130-250 degrees C) is blown towards the exposed upper surface of the otherwise entirely closed core. This happens while the cylinder is standing on a balance, which allows very frequent measurements of total weight. For validity of the mathematical assumptions used in the calculations, the loss of weight must be proportional to the square root of time as well as the lower part of the core should remain at the original water content. As soon as the hot air is turned off, the core is gently pushed from the cylinder and is cut in small, 2-5 cm thick sections from which the gravimetric moisture content is determined. A graph of water content versus depth is used in calculating diffusivity.

Parameters measured-- Diffusivity (cm^2 sec^{-1})

Method-- (Arya et al., 1975).

Apparatus: The only equipment required for this method are: (1) hot air gun, (2) brass cylinders 10 cm high and 5 cm in diameter, and (3) a balance.

Procedure:

(1) Field soils are sampled by pushing brass cylinders vertically into the soil, which are then excavated and carefully trimmed at both ends.

(2) Samples are then placed on porous ceramic discs in the laboratory in contact with free water to allow saturation by capillary action.

(3) Samples are then sealed at both ends and positioned horizontally to equilibrate for several days.

(4) Then the core is opened on one end and placed on a balance. Hot air is then blown on the open wet surface for 10 - 25 minutes to achieve maximum evaporation.

(5) Water loss due to evaporation is determined by subsequent weighing of the soil core during the procedure. Such loss in weight as a function of time serves as a check of one condition presupposed by the method, which says that a cumulative evaporation must be proportional to the square root of time.

(6) At the conclusion of each test the bottom seal of the core is broken and the soil is pushed out of the brass cylinder with a suitably designed piston.

(7) Within minutes the core is sliced into several (12 - 15) 2 - 5 mm lengths which are weighed and oven dried to determine the gravimetric water content distribution and the average bulk density. The water contents of the lower segments proved if a second condition is met, i. e., that the original water content of the soil column was maintained unchanged at the closed end during the evaporation procedure.

(8) Next, the volume of each sample is estimated by dividing its dry weight by the mean bulk density of the soil core. Sample length is obtained by dividing the sample volume by the internal cross-sectional area of the brass cylinder

(9) With this information the following graph can be developed:

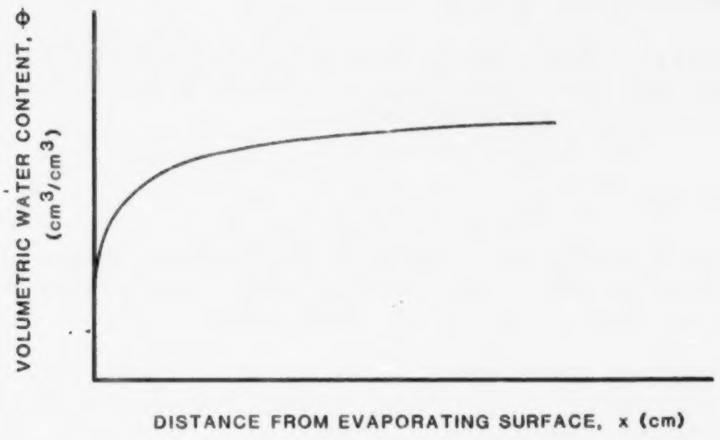


Figure 6.27 Graph of volumetric water content versus distance from evaptorating surface.

(10) From such a smoothed water content distribution curve, diffusivity can be calculated according to the equation (Bruce and Klute, 1956):

$$D(\theta_x) = \frac{1}{2t}\,(dx/d\theta)\,\theta_x \int_{\theta_x}^{\theta_i} x\,d\theta$$

where

$D(\theta_x)$ = the diffusivity as a function of the volumetric water content, θ, in cm^2 sec^{-1}
t = time, in seconds
x = the distance from the evaporating surface, in cm
θ_i = the initial water content, in cm^3/cm^3

Boundary conditions are:

$\theta = \theta_i$ $x > \theta$ $t = \theta$

$\theta = \theta_o$ $x = \theta$ $t > \theta$

where θ_o is the air dry water content.

Precision and accuracy-- The precision of this method is only fair because of the dependence on the slope of the graph, the determination of gravimetric moisture contents, and small sample size. The accuracy is good for strictly matrix flow, but only fair overall because of small sample size.

Limitations of test-- (1) Small sample size can be unrepresentative of field conditions; (2) Requires moisture retention curve to calculate unsaturated hydraulic ocnductivity; (3) Method is not very reliable near saturation due to difficulties in determining slopes of $d\theta/dx$ lines in the lower part of the core; and (4) The method seems to be limited to soils and soil structures with relatively low conductivities in the low tension range.

Status of the method-- Relatively new test but its use is increasing due to the fact that the method is simple, rapid, and inexpensive.

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SECTION 7

SUMMARY

The conclusions that can be drawn from this study are: (1) The area of soil testing for hydraulic conductivity overlaps the professions of geology, hydrology, soil engineering, and soil science as all these disciplines have made attempts to measure the rate of liquid movement thru soil materials; (2) A high percentage of the testing methods for hydraulic conductivity determination have been developed for agricultural or engineering purposes other than the application to the feasibility and/or design of hazardous waste disposal sites; (3) All laboratory methods suffer from potential misrepresentation of actual field conditions due to small size of samples and/or disruption of samples when transported or remixed; (4) Experience with field testing techniques has generally been limited to more coarse-textured soils rather than fine-grained soils that are more appropriate for hazardous waste disposal sites; (5) It is not possible at this time to discern the degree of variation in soil testing results caused by the variation inherent in the soil testing method compared to the variation of the spatial properties of the soil itself; and (6) Determination of soil hydraulic conductivity values is the limiting factor to further development of an applicable saturated - unsaturated transport model for prediction or estimation of behavior of a proposed hazardous waste disposal site.

Important considerations and limitations of laboratory and field testing methods are summarized in the Soil Testing Methods Matrix which are shown in Tables 7.1 and 7.2. Table 7.1 summarizes information for laboratory and field methods for the determination of saturated hydraulic conductivity while Table 7.2 is directed at unsaturated hydraulic conductivity methods, calculation methods, and diffusivity methods.

TABLE 7-1 SOIL TESTING METHODS MATRIX/SATURATED HYDRAULIC CONDUCTIVITY

METHOD		APPLICATION	PRECISION AND ACCURACY
SATURATED / Laboratory	PRESSURE CELL	Land treatment	Fair-many samples necessary to obtain 95% confidence limits
	COMPACTION MOLDS	Liner evaluation	Not available (new method)
	CONSOLIDATION CELL	Liner evaluation	Fair-direct measurement of consolidated sample is much more precise than K computed from consolidation and compression data
	MODIFIED TRIAXIAL APPARATUS	Liner evaluation	Good-reproducible results
SATURATED / Field	PIEZOMETERS	Land treatment	Fair-measure average of vertical and horizontal components of K in all soil layers below water table
	DOUBLE RING INFILTROMETER /PERMEAMETER	Land treatment	Good-reproducible results
	AIR-ENTRY PERMEAMETER	Land treatment	Good-reproducible results that compare favorably with other methods
	CUBE	Land treatment	Good-large size of sample more representative of in situ conditions, can measure vertical and horizontal K separately
	CRUST	Land treatment	Good-large sample size and reproducible results, can measure both saturated and unsaturated K

LIMITATIONS OF TEST	METHOD STATUS	COMMENTS
(1) Small sample may be unrepresentative of actual field conditions, (2) several days required for fine-textured soils, and (3) saturation of sample not assured	Agricultural standard	Simple and inexpensive equipment
(1) Small sample, (2) excessive gradients may cause sidewall flow, (3) interaction between metal cell and waste, (4) saturation of sample not assured, and (5) test will take 1-5 months	Experimental	Special equipment developed for use of particular waste and compacted soil
(1) Small sample, (2) falling head procedure may require many days to perform test, and (3) saturation of sample not assured	Engineering standard for consolidation data	Slight modification of common engineering laboratory equipment
(1) Small sample, and (2) recommended hydraulic gradients in range of 5-20	Engineering standard, common for clay soils with low hydraulic conductivity	Major modification of common engineering laboratory equipment
(1) Errors due to smear zones, (2) requires presence of water table, and (3) measures both vertical and horizontal hydraulic conductivity	Standard test for areas with shallow depths to water table	Many variations in equipment and and procedures
(1) Care must be taken during placement of rings into soil, (2) air trapped below wetting front will effect results, (3) a few days required for fine-textured soils, and (4) if uncovered, correction for evaporation should be made	ASTM standard, also commonly used in agriculture and irrigation	Simple and inexpensive equipment, easy method to perform
(1) Care must be taken during placement of cylinder into soil, (2) will not work well on initially wet soils, and (3) difficult on soils with gravel or stones	Relatively new method, use increasing due to ease of procedure	Moderately inexpensive equipment
(1) Method will require a few days for clay soils, (2) sample saturation cannot be assured, and (3) swelling of sample may effect measurement	Relatively new method, use increasing due to ease of procedure	Very inexpensive equipment and materials
(1) Difficult to assure good contact between soil pedestal and ring	Relatively new method, developed in connection with EPA sponsered university research	Moderately inexpensive equipment, easy to perform for saturated K

TABLE 7-2 SOIL TESTING METHODS MATRIX/UNSATURATED HYDRAULIC CONDUCTIVITY

METHOD		APPLICATION	PRECISION AND ACCURACY
UNSATURATED / Laboratory	STEADY STATE / COLUMN	Unsaturated zone	Fair-variability decreases as length of column increases
	UNSTEADY STATE / INSTANTANEOUS PROFILE	Unsaturated zone	Fair-many variations of method, field method more accurate
	THERMOCOUPLE PSYCHROMETERS	Unsaturated zone	Good-accuracy of, and range of suction of psychrometers makes method particularly applicable to compacted arid soils
UNSATURATED / Field	CRUST	Unsaturated zone	Good-large sample size and reproducible results, can measure both saturated and unsaturated K
	INSTANTANEOUS PROFILE	Unsaturated zone	Good-probably the most accurate field method because of the large sample size
CALCULATION METHODS	VARIOUS PROCEDURES	Unsaturated zone	Fair-calculated values never as good as measured values
DIFFUSIVITY	PRESSURE OUTFLOW	Unsaturated zone	Fair-disagreement among authors regarding precision and accuracy
	HOT AIR	Unsaturated zone	Fair-because of dependence on the slope of the water content curve and determination of water contents gravimetrically

LIMITATIONS OF TEST	METHOD STATUS	COMMENTS
(1) Method will require longer time for clay soils, (2) small sample, (3) procedure yields K(h), not K(θ), (4) K determined from desorption rather than absorption data, and (5) suction limited to range of tensiometer measurement	Agricultural standard	Inexpensive equipment
(1) Method will require longer time for clay soils, (2) small sample, and (3) results limited to range of tensiometer measurement	Agricultural standard	Expensive and potentially dangerous equipment, detailed procedure
(1) Small sample, (2) applicable to clays with degrees of saturation between 30-90%, and sands less than 50%, (3) psychrometer corrosion in acid soils, and (4) cannot measure K near saturation	Experimental	Moderately expensive equipment, detailed procedure
(1) Several days required to achieve steady state flow under crusts of high resistance, (2) difficult to assure good contact between soil pedestal and ring, and (3) results limited to range of tensiometer measurement	Relatively new method, developed in connection with EPA sponsored university research	Moderately inexpensive equipment, repetitive procedure with crusts of different resistance
(1) Results limited to range of tensiometer measurement, (2) field plot must be level, (3) not applicable in soils with high lateral flow, and (4) plots should be larger if surrounding area is strongly evapotranspiring	Agricultural standard	Moderately expensive equipment, easy procedure once set up
(1) Limited to more coarse-textured soils, (2) matching factors must be determined, and (3) matching factors most often determined at or near saturation	Experimental	Large variety of methods
(1) Small sample, and (2) many variations of method using disturbed and undisturbed samples, inflow rather than outflow measured, or one large pressure increment used instead of several small ones	Agricultural and ASTM standard	Moderately inexpensive equipment, detailed procedure
(1) Small sample, (2) requires moisture retention curve to calculate K, (3) not very reliable near saturation, and (4) limited to soils with relatively low conductivities in the low tension range	Relatively new method, use increasing due to short time period for test	Inexpensive equipment, easy procedure

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APPENDIX A

GLOSSARY OF TECHNICAL TERMS

absorption: The process by which one substance is taken into and included within another substance, as the absorption of water by soil or nutrients by plants. (2)

acidity, total: The total acidity in a soil or clay. Usually it is estimated by a buffered salt determination of (cation-exchange minus exchangeable bases) = total acidity. (1)

adsorption: The increased concentration of molecules or ions at a surface, including exchangeable cations and anions on soil particles. (2)

aggregation: The act of soil particles cohering so as to behave mechanically as a unit. (2)

air-dry: (a) The state of dryness (of a soil) at equilibrium with the moisture content in the surrounding atmosphere. The actual moisture content will depend upon the relative humidity and the temperature of the surrounding atmosphere. (b) To allow to reach equilibrium in moisture content with the surrounding atmosphere. (1)

alkaline soil: Any soil having a pH > 7.0. (1)

anisotropic mass: A mass having different properties in different directions at any given point. (5)

available water: The portion of water in a soil that can be readily absorbed by plant roots. Considered by most workers to be that water held in the soil against a pressure of up to approximately 15 bars. (1)

bar: A unit of pressure equal to one million dynes per square centimeter. (1)

base-saturation percentage: The extent to which the adsorption complex of a soil is saturated with exchangeable cations other than hydrogen. It is expressed as a percentage of the total cation-exchange capacity. (1)

bearing capacity: Ability of a material to support a load normal to the surface. (6)

bedrock: The more or less continuous body of rock which underlies the overburden soils. (7)

bentonite: An expansive clay formed from the decomposition of volcanic ash. (6)

bulk density, soil: The mass of dry soil per unit bulk volume. The bulk volume is determined before drying to constant weight at 105 degrees Centigrade. (1)

bulk specific gravity: The ratio of the bulk density of a soil to the mass of unit volume of water. (1)

bulk volume: The volume, including the solids and the pores, of an arbitrary soil mass. (1)

California bearing ratio: The ratio of: (1) The force per unit area required to penetrate a soil mass with a 3 square inch (8 cm) circular piston (approximatelly 1.95 inch (51 mm) diameter) at the rate of 0.05 inches (1.3 mm)/minute, to (2) That required for corresponding penetration of a standard material. The ratio is usually determined at 0.1 inch (12.7 mm). Corps of Engineers' procedures require determination of the ratio at 0.1 inch and 0.2 inch (5.1 mm). Where the ratio of 0.2 inch is consistently higher that at 0.1 inch, the ratio at 0.2 inch is used. (5)

capillary attraction: A liquid's movement over or retention by a solid surface due to the interaction of adhesive and cohesive forces. (1)

capillary conductivity: (Obsolete) See soil water - B: hydraulic conductivity.

capillary fringe: A zone just above the water table (zero gauge pressure) that remains almost saturated. (The extent and the degree of definition of the capillary fringe depends upon the size-distribution of pores). (1)

capillary migration (capillary flow): The movement of water by capillary action. (5)

cation-exchange: The interchange between a cation and solution and another cation on the surface of any surface-active material such as clay colloid or organic colloid. (1)

cation-exchange capacity (CEC): The sum total of exchangeable cations that a soil can absorb. Expressed in milliequivalents per 100 grams or per gram of soil (or of other exchangers such as clay). (1)

channels: Voids that are significantly larger than packing voids. They are generally cylindrically shaped and smooth walled, have regular conformation, and have relatively uniform cross-sectional size and shape. (4)

clay: (a) A soil separate consisting of particles > 0.002 mm in equivalent diameter. (b) A textural class. (1)

clay films: Coating of clay on the surfaces of soil peds and mineral grains and in soil pores. (Also called clay skins, clay flows, illuviation cutans, argillans or tonhautchen.) (1)

clay mineral: Naturally occurring inorganic crystalline material found in soils and other earthy deposits, the particles being clay sized; that is, > 0.002 mm in diameter. (1)

clod: A compact, coherent mass of soil ranging in size from 5 to 100 mm to as much as 20 to 25 cm and is produced artificially usually by the activity of man by plowing, digging, etc., especially when these operations are performed on soils that are either too wet or too dry for normal tillage operations. (1)

coarse fragments: Rock or mineral particles > 2.0 mm in diameter. (1)

coarse texture: The texture exhibited by sand, loamy sands, and sandy loams except very fine sandy loams. (1)

cohesionless soil: A soil that when unconfined has little or no strength when air-dried and that has little or no cohesion when submerged. (5)

cohesive soil: A soil that when unconfined has considerable strength when air-dried and that has significant cohesion when submerged. (5)

colloidal particles: Particles that are so small that the surface activity has an appreciable influence on the properties of the particle. (1)

compaction: The densification of a soil by means of mechanical manipulation. (5)

compaction curve (Proctor curve) (moisture-density curve): The curve showing the relationship between the dry unit weight (density) and the water content of a soil for a given compactive effort. (5)

compaction test (moisture-density test): A laboratory compacting procedure whereby a soil at a known water content is placed in a specified manner into a mold of given dimensions, subjected to a compactive effort of controlled magnitude, and the resulting unit weight is determined. The procedure is repeated for various water contents sufficient to establish a relation between water content and unit weight. (5)

compressibility: Property of a soil or rock pertaining to its susceptibility to decrease in volume when subjected to load. (5)

compression curve: See pressure-void ratio curve.

compressive strength (unconfined or uniaxial compressive strength): The load per unit area at which an unconfined cylindrical specimen of soil or rock will fail in a simple compression test. Commonly the failure load is the maximum that the specimen can withstand in the test. (5)

conductivity, hydraulic: See soil water.

consistency: (a) The resistance of a material to deformation or rupture. (b) The degree of cohesion or adhesion of the soil mass. (1)

consolidation: The gradual reduction in volume of a soil mass resulting from an increase in compressive stress. (a) initial consolidation (initial compression): A comparatively sudden reduction in volume of a soil mass under an applied load due principally to expulsion and compression of gas in the soil voids preceding primary consolidation. (b) primary consolidation (primary compression) (primary time effect): The reduction in volume of a soil mass caused by the application of a sustained load to the mass and due principally to a squeezing out of water from the void spaces of the mass and accompanied by a transfer of the load from the soil water to the soil solids. (c) secondary consolidation (secondary compression) (secondary time effect): The reduction in volume of a soil mass caused by the application of a sustained load to the mass and due principally to the adjustment of the internal structure of the soil mass after most of the load has been transferred from the soil water to the soil solids. (5)

consolidation test: A test in which the specimen is laterally confined in a ring and is compressed between porous plates. (5)

consolidation-time curve (time curve) (consolidation curve) (theoretical time curve): A curve that shows the relation between: (1) The degree of consolidation, and (2) The elapsed time after the application of a given increment of load. (5)

creep: Slow mass movement of soil and soil material down relatively steep slopes primarily under the influence of gravity, but facilitated by saturation with water and by alternate freezing and thawing. (1)

crust: A surface layer on soils, ranging in thickness from a few millimeters to perhaps as much as an inch, that is much more compact, hard, and brittle, when dry, than the material immediately beneath it. (1)

cutan: A modification of the texture, structure, or fabric at natural surfaces in soil materials due to concentration of particular soil constituents or 'in-situ' modification of the plasma; cutans can be composed of any of the component substances of the soil material. (4)

Darcy's law: (a) A law describing the rate of flow of water through porous media. (Named for Henry Darcy of Paris who formulated it in 1856 from extensive work on the flow of water through sand filter beds.) As formulated by Darcy the law is:

$$Q = \frac{kS(H + e)}{e}$$

where

Q is the volume of water passed in unit time,
S is the area of the bed,
e is the thickness of the bed,
H is the height of the water on top of the bed, and
"k is a coefficient depending on the nature of the sand" and for cases where the pressure "under the filter is equal to the weight of the atmospheres"

(b) Generalization for three dimensions: The rate of viscous flow of water in isotrophic porous media is proportional to, and in the direction of, the hydraulic gradient. (c) Generalization for other fluids: The rate of viscous flow of homogenous fluids through isotrophic porous media is proportional to, and in the direction of, the driving force. (1)

deflocculate: (a) To separate the individual components of compound particles by chemical and/or physical means. (b) To cause the particles of the disperse phase of a colloidal system to become suspended in the dispersion medium. (1)

deformation: A change in the shape or size of a solid body. (7)

degradation: The breakdown of substances by biological action. (2)

degree of consolidation (percent consolidation): The ratio, expressed as a percentage of: (1) The amount of consolidation at a given time within a soil mass, to (2) The total amount of consolidation obtainable under a given stress condition. (5)

degree of saturation: The extent or degree to which the voids in rock contain fluid (water, gas, or oil). Usually expressed in percent related to total void or pore space. (7)

deposit: Material left in a new position by a natural transporting agent such as water, wind, ice, or gravity, or by the activity of man. (1)

depression curve: Record of profile of water table as a result of pumping. (6)

discontinuity: (a) Boundary between major layers of the Earth which have different seismic velocities. (b) Interruption of the homogeneity of a rock mass (e.g. joints, faults, etc.). (5)

disperse: (a) To break up compound particles, such as aggregates, into the individual component particles. (b) To distribute or suspend fine particles, such as clay, in or throughout a dispersion medium, such as water . (1)

disturbed samples: Soil samples obtained in a manner which destroys the original orientation and some of the physical properties of the naturally disposed material. (6)

drawdown curve: The trace of the top surface of the water table in an aquifer or of the free water surface, when a new or changed means of extraction of water takes place. (6)

dry-weight percentage: The ratio of the weight of any constituent (of a soil) to the oven-dry weight of the soil. See oven-dry soil. (1)

ductility: The condition in which material can sustain permanent deformation without losing its ability to resist load. (7)

duripan: A mineral soil horizon that is cemented by silica, usually opal or micro-crystalline forms of silica, to the point that air-dry fragments will not slake in water or HCl. A duripan may also have accessory cement such as iron oxide or calcium carbonate. (1)

elastic limit: Point on stress-strain curve at which transition from elastic to inelastic behavior takes place. (7)

eolian: Pertaining to material transported and deposited by the wind. Includes earth materials ranging from dune sands to silty loess deposits. (3)

equivalent diameter: In sedimentation analysis, the diameter assigned to a non-spherical particle, it being numerically equal to the diameter of a spherical particle of the same density and velocity of fall. (1)

erode: To wear away or remove the land surface by wind, water, or other agents. (1)

evapotranspiration: The combined loss of water from a given area, and during a specified period of time, by evaporation from the soil surface and by transpiration from plants. (1)

fabric (soils): The physical constitution of a soil material as expressed by the spatial arrangement of the solid particles and associated voids. Fabric is the element of structure which deals with arrangement. (4)

failure (in rocks): Exceeding the maximum strength of the rock or exceeding the stress or strain requirement of a specific design. (7)

fault: A fracture or fracture zone along which there has been displacement of the two sides relative to one another parallel to the fracture (this displacement may be a few centimeters or many kilometers). (7)

field capacity (field moisture capacity): (Obsolete in technical work.) The percentage of water remaining in a soil 2 or 3 days after having been saturated and after free drainage has practically ceased. (The percentage may be expressed on the basis of weight or volume.) See moisture tension. (1)

fill: Man-made deposits of natural soils or rock products and waste materials. (5)

film water: A layer of water surrounding soil particles and varying in thickness from 1 or 2 to perhaps 100 or more molecular layers. Usually considered as that water remaining after drainage has occurred because it is not distinguishable in saturated soils. (1)

fine texture: Consisting of or containing large quantities of the fine fractions, particularly of silt and clay. (Includes all clay loams and clays; that is, clay loams, sandy clay loam, silty clay loam, sandy clay, silty clay, and clay textural classes. Sometimes subdivided into clayey texture and moderately fine texture.) See soil texture. (1)

firm: A term describing the consistency of a moist soil that offers distinctly noticeable resistance to crushing but can be crushed with moderate pressure between the thumb and forefinger. See consistency. (1)

fissure flow: Flow of water through joints and larger voids. (5)

flow curve: The locus of points obtained from a standard liquid limit test and plotted on a graph representing water content as ordinate on an arithmetic scale and the number of blows as abscissa on a logarithmic scale. (5)

flow line: The path that a particle of water follows in its course of seepage under laminar flow conditions. (5)

flow net: A graphical representation of flow lines and equipotential (piezometric) lines used in the study of seepage phenomena. (5)

fracture: A break in the mechanical continuity of a body of rock caused by stress exceeding the strength of the rock. Includes joints and faults. (5)

fragipan: A natural subsurface horizon with high bulk density relative to the solum above, seemingly cemented when dry, but when moist showing a moderate to weak brittleness. The layer is low in organic matter, mottled, slowly or very slowly permeable to water, and usually shows occasional or frequent bleached cracks forming polygons. It may be found in profiles of either cultivated or virgin soils but not in calcareous material. (1)

free water (gravitational water) (ground water) (phreatic water): Water that is free to move through a soil or rock mass under the influence of gravity. (5)

friable: A consistency term pertaining to the ease of crumbling of soils. See consistency. (1)

geohydrology: Science of the occurrence, distribution, and movement of water below the surface of the Earth. (6)

geomorphology: The description of the present exposed surfaces of the crust of the Earth, and seeks to interpret these surfaces in terms of natural processes (chiefly erosion) which lead or have led to their formation. (6)

geophysics: The study of all the gross physical properties of the Earth and its parts, particularly associated with the detection of the nature and shape of unseen subsurface rock bodies by measurement of such properties and property contrasts. Small scale applied geophysics is now a major aid in geological reconnaissance. (6)

geotechnical: Pertaining to geotechnics, which is the application of scientific methods to problems in engineering geology. (6)

glacial drift: Rock debris that has been transported by glaciers and deposited, whether directly from the ice or from the meltwater. The debris may or may not be heterogeneous. (1)

glacial geology: The study of the direct effects of the formation and flow under gravity of large ice masses on the Earth's surface. Glaciology is concerned with the physics of ice masses. (6)

glacial outwash: Stratified sand and gravel produced by glaciers and carried, sorted, and deposited by water that originated mainly from the melting of glacial ice. Outwash deposits may occur in the form of valley fills (valley trains and/or outwash terraces) or as widespread outwash plains. (3)

glaciofluvial deposits: Material moved by glacier and subsequently sorted and deposited by streams flowing from the melting ice. (3)

glaciolacustrine deposits: Material ranging from fine clay to sand derived from glaciers and deposited in glacial lakes by water originating mainly from the melting of glacial ice. Many are bedded or laminated with varves. (3)

glacial till: Unsorted and unstratified glacial drift, generally unconsolidated, deposited directly by a glacier without subsequent reworking by water from the glacier, and consisting of a heterogeneous mixture of clay, silt, sand, gravel, and boulders varying widely in size and shape. (3)

gleying: Formation of gray or green material in soil when stagnation of water results in exclusion of air and reduction of iron. (6)

gradation (grain-size distribution) (texture): The proportions by mass of a soil or fragmented rock distributed in specified particle-size ranges. (5)

grading: A 'well-graded' sediment containing some particles of all sizes in the range concerned. Distinguish from 'well-sorted', which describes a sediment with grains of one size. (6)

grain-size analysis (mechanical analysis) (particle-size analysis): The process of determining grain-size distribution. (5)

granule: A natural soil aggregate or ped which is relatively nonporous. See soil structure and soil structure types. (1)

gravel: Round or semirounded particles of rock that will pass a 3-in. (76.2 mm) sieve and be retained on a No. 4 (4.75 mm) U.S. standard sieve. (5)

gravitational potential: See soil water.

ground water: The portion of the total precipitation which at any particular time is either passing through or standing in the soil and the underlying strata and is free to move under the influence of gravity. (1)

ground water level: The level below which the rock and subsoil, to unknown depths, are saturated. (7)

hardpan: A hardened soil layer, in the lower A or in the B horizon, caused by cementation of soil particles with organic matter or with materials such as silica, sesquioxides, or calcium carbonate. The hardness does not change appreciably with changes in moisture content and pieces of the hard layer do not slake in water. (1)

head: The energy, either kinetic or potential, possessed by each unit weight of a liquid, expressed as the vertical height through which a unit weight would have to fall to release the average energy possessed. It is used in various compound terms such as pressure head, velocity head, and loss of head. (2)

heave: Upward movement of soil caused by expansion or displacement resulting from phenomena such as: moisture absorption, removal of overburden, driving of piles, frost action, and loading of an adjacent area. (5)

heterogeneity: Having different properties at different points. (7)

homogeneous mass: A mass that exhibits essentially the same physical properties at every point throughout the mass. (5)

horizon: See soil horizon.

hydration: The physical binding of water molecules to ions, molecules, particles, or other matter. (2)

hydraulic conductivity: See soil water.

hydraulic gradient: The loss of hydraulic head per unit distance of flow. (5)

hydrogeology: The study of the natural (and artificial) distribution of water in rocks, and its relationship to those rocks. Inasmuch as the atmosphere is a continuation of the hydrosphere, and is in physical and chemical balance with it, there is a close connection with meteorology. (6)

hydrostatic pressure: A state of stress in which all the principal stresses are equal (and there is no shear stress). (7)

hygroscopic water: Water adsorbed by a dry soil from an atmosphere of high relative humidity, water remaining in the soil after "air-drying" or water held by the soil when it is in equilibrium with an atmosphere of a specified relative humidity at a specified temperature, usually 98% of relative humidity at 25 degrees Centigrade. (1)

igneous rock: Rock formed from the cooling and solidification of magma, and that has not been changed appreciably since its formation. (1)

immobilization: The conversion of an element from the inorganic to the organic form in microbial tissues or in plant tissues. (1)

impervious: Resistant to penetration by fluids or by roots. (1)

infiltration: The downward entry of water into the soil. (1)

infiltration rate: A soil characteristic determining or describing the maximum rate at which water can enter the soil under specified conditions, including the presence of an excess of water. (1)

integral sampling: A technique of core drilling which provides knowledge of the original orientation of the samples recovered. (6)

intergrade: A soil that possesses moderately well-developed distinguishing characteristics of two or more genetically related soil Great Groups. (1)

internal friction (shear resistance): The portion of the shearing strength of a soil or rock that is usually considered to be due to the interlocking of the soil or rock grains and the resistance to sliding between the grains. (5)

ion exchange: A chemical process involving reversible interchange of ions between a liquid and a solid but no radical change in structure of the solid. (2)

isochrome: A curve showing the distribution of the excess hydrostatic pressure at a given time during a process of consolidation. (5)

isomorphous substitution: The replacement of one atom by another of similar size in a crystal lattice without disrupting or changing the crystal structure of the mineral. (1)

isotropic: Having the same properties in all directions. (6)

joint: A break of geological origin in the continuity of a body of rock occurring either singly, or more frequently in a set or system, but not attended by a visible movement parallel to the surface of discontinuity. (7)

kame: A moundlike hill of ice-contact glacial drift, composed chiefly of stratified sand and gravel. (3)

karst: A type of topography that is characterized by closed depressions or sink holes, and is dependent upon underground solution and the diversion of surface waters to underground routes. It is formed over limestone, dolomite, gypsum and other soluble rocks as a result of differential solution of these materials and associated processes of subsurface drainage, cave formation, subsidence, and collapse. (3)

laminar flow (streamline flow) (viscous flow): Flow in which the head loss proportional to the first power of the velocity. (5)

landform: Any physical, recognizable form or feature of the Earth's surface, having a characteristic shape, and produced by natural causes. (3)

landscape: All the natural features, such as fields, hills, forests, and water that distinguish one part of the Earth's surface from another part; usually that portion of land or territory which the eye can comprehend in a single view, including all of its natural characteristics. The distinct association of landforms, especially as modified by geologic forces, that can be seen in a single view. (3)

leach: To cause water or other liquid to percolate through soil. (2)

line of seepage (seepage line) (Phreatic line): The upper free water surface of the zone of seepage. (5)

liquefaction: Act or process of liquefying or of rendering or becoming liquid; reduction to a liquid state. (2)

liquid limit: The minimum percentage (by weight) of moisture at which a small sample of soil will barely flow under a standard treatment. Synonymous with "upper plastic limit". See plastic limit. (1)

liquidity index (water-plasticity ratio) (relative water content): The ratio, expressed as a percentage, of (1) The natural water content of a soil minus its plastic limit, to (2) its plasticity index. (5)

lithologic: Pertaining to the physical character of a rock. (3)

loading: The time rate at which material is applied to a treatment device involving length, area, volume or other design factor. (1)

loess: Material transported and deposited by wind and consisting of predominantly silt-sized particles. (1)

lysimeter: (a) A device for measuring percolation and leaching losses from a column of soil under controlled conditions. (b) A device for measuring gains (precipitation and condensation) and losses (evapotranspiration) by a column of soil. (1)

manometer: An instrument for measuring pressure. It usually consists of a U-shaped tube containing a liquid, the surface of which in one end of the tube moves proportionally with changes in pressure on the liquid in the other end. Also, a tube type of differential pressure gauge. (2)

matric potential: See potential, soil water.

mechanical analysis: (Obsolete) See particle-size analysis and particle-size distribution.

mesh: One of the openings or spaces in a screen. The value of the mesh is usually given as the number of openings per linear inch. This gives no recognition to the diameter of the wire and thus mesh number does not always have a definite relation to the size of the hole. (2)

metamorphic rock: Rock derived from pre-existing rocks but that differ from them in physical, chemical, and mineralogical properties as a result of natural geological processes, principally heat and pressure, originating in the Earth. The pre-existing rocks may have been igneous, sedimentary, or another form of metamorphic rock. (1)

modulus of elasticity (modulus of deformation): The ratio of stress to strain for a mineral under given loading condition; numerically equal to the slope of the tangent or the secant of a stress-strain curve. (5)

moisture content (water content): The ratio, expressed as a percentage, of: (a) The weight of water in a given soil mass, to (b) The weight of solid particles. (5)

moisture-retention curve: A graph showing the soil moisture percentage (by weight or by volume) versus applied tension (or pressure). Points on the graph are usually obtained by increasing (or decreasing) the applied tension or pressure over a specified range. (1)

moraine: An accumulation of drift, with an initial topographic expression of its own, built chiefly by the direct action of glacial ice. Examples are end, ground, lateral, recessional, and terminal moraines. (3)

morphology: See soil morphology.

N-value: The number of blows required to drive the sampler of the Standard Penetration test its last 12 inches (300 mm). (6)

negative pressure: A pressure less than the local atmospheric pressure at a given point. (3)

normally consolidated soil deposit: A soil deposit that has never been subjected to an effective pressure greater than the existing overburden pressure. (5)

optimum moisture content (optimum water content): The water content at which a soil can be compacted to a maximum dry unit weight by a given compactive effort. (5)

osmotic pressure: See soil water.

outwash plain: An extensive lowland area forming the surface of a body of coarse textured, glaciofluvial material. An outwash plain is commonly smooth; where pitted, due to melt-out of incorporated ice masses, it is generally low in relief. (3)

oven-dry soil: Soil which has been dried at 105 degrees Centigrade until it reaches constant weight. (1)

overburden: The loose soil, sand, silt, or clay that overlies bedrock. (7)

overburden load: The load on a horizontal surface underground due to the column of material located vertically above it. (7)

overconsolidated soil deposit: A soil deposit that has been subjected to an effective pressure greater than the present overburden pressure. (5)

oxidation-reduction potential: The potential required to transfer electrons from the oxidant to the reductant and used as a qualitative measure of the state of oxidation in wastewater treatment systems. (2)

parent material: The unconsolidated and more or less chemically weathered mineral or organic matter from which the solum of soil is developed by pedogenic processes. (1)

particle density: The mass per unit volume of the soil particles. In technical work, usually expressed as grams per cubic centimeter. See bulkeny, soil. (1)

particle size: The effective diameter of a particle measured by sedimentation, sieving, or micrometric methods. (1)

particle-size analysis: Determination of the various amounts of the different separates in a soil sample, will usually be sedimentation, sieving, micrometry, or combinations of these methods. (1)

particle-size distribution: The amounts of the various soil separates in a soil sample, usually expressed as weight percentages. (1)

ped: An individual natural soil aggregate consisting of a cluster of primary particles, and separated from adjoining peds by surfaces of weakness which are recognizable as natural voids or by the occurrence of cutans. (4)

pedology: (a) The description of those parts of the present Earth surface which have become weathered or otherwise modified 'in-situ' by solar energy and by the effects of organisms to form a soil which is of primary importance to man in agriculture. (6) (b) The science of soils, that is, the study of the origin, classification, description and use of natural soil bodies. (4)

pedon: A three-dimensional body of soil with lateral dimensions large enough to permit the study of horizon shapes and relations. Its area ranges from 1 to 10 square meters. Where horizons are intermittent or cyclic, and recur at linear intervals of 2 to 7 m, the pedon includes one-half of the cycle. Where the cycle is less than 2 m, or all horizons are continuous and of uniform thickness, the pedon has an area of approximately 1 square meter. If the horizons are cyclic, but recur at intervals greater than 7 m, the pedon reverts to the 1 square meter size, and more than one soil will usually be represented in each cycle. (1)

penetrability: The ease with which a probe can be pushed into the soil. (May be expressed in units of distance, speed, force, or work depending on the type of penetrometer used. (1)

penetration resistance (standard penetration resistance) (Proctor penetration resistance): (a) A number of blows of a hammer of specified weight falling a given distance required to produce a given penetration into soil of a pile, casing, or sampling tube. (b) Unit load required to maintain constant rate of penetration into soil of a probe or instrument. (c) Unit load required to produce a specified penetration into soil at a specified rate of a probe or instrument. For a Proctor needle, the specified penetration is 2.5 in. (63.5 mm) and the rate is 0.5 in. (12.7mm)/sec. (5)

penetration resistance curve (Proctor penetration curve): The curve showing the relationship between: (a) The penetration resistance, and (b) The water content. (5)

percent compaction: The ratio, expressed as a percentage, of: (a) Dry unit weight of a soil, to (b) Maximum unit weight obtained in a laboratory compacton test. (5)

percent saturation (degree of saturation): The ratio, expressed as a percentage, of: (a) The volume of water in a given soil or rock mass, to (b) The total volume of intergranular space (voids). (5)

perched water table: A water table usually of limited area maintained above the normal free water elevation by the pressure of an intervening relatively impervious confining stratum. (5)

percolation: The flow or trickling of a liquid downward through a contact or filtering medium. The liquid may or may not fill the pores of the medium. (2)

permanent strain: The strain remaining in a solid with respect to its initial condition after the application and removal of stress greater than the yield stress (commonly also called "residual" strain). (7)

permeability, soil: (a) The ease with which gases, liquids, or plant roots penetrate or pass through a bulk mass of soil or a layer of soil. Since different soil horizons vary in permeability, the particular horizon under question should be designated. (b) The property of a porous medium itself that relates to the ease with which gases, liquids, or other substances can pass through it. Previously, frequently considered the "k" in Darcy's law. See Darcy's law and soil water. (1)

pH, soil: The negative logarithm of the hydrogen-ion activity of a soil. The degree of acidity (or alkalinity) of a soil as determined by means of a glass, quinhydrone, or other suitable electrode or indicator at a specified moisture content or soil-water ratio, and expressed in terms of the pH scale. (1)

physical properties (of soil): Those characteristics, processes, or reactions of a soil which are caused by physical forces and which can be described by, or expressed in, physical terms or equations. Sometimes confused with and difficult to separate from chemical properties; hence, the terms "physical-chemical" or "physiochemical". Examples of physical properties are bulk density, water-holding capacity, hydraulic conductivity, porosity, pore-size distribution, etc. (1)

piezometer: An instrument for measuring pressure head. (5)

piezometric surface: (a) The surface at which water will stand in a series of piezometers. (5) (b) An imaginary surface that everywhere coincides with the static level of the water in the aquifer. (7)

piping: An underground flow of water with a sufficient pressure gradient to cause scour along a preferred path. (6)

piston sampler: A tube with an internal piston used for obtaining relatively undisturbed samples from cohesive soils. (6)

plane of weakness: Surface or narrow zone with a (shear or tensile) strength lower than that of the surrounding material. (7)

plane stress (strain): A state of stress (strain) in a solid body in which all stress (strain) components normal to a certain plane are zero. (7)

plastic equilibrium: State of stress within a soil or rock mass or a portion thereof, which has been deformed to such an extent that its ultimate shearing resistance is mobilized. (5)

plastic flow (plastic deformation): The deformation of a plastic material beyond the point of recovery, accompanied by continuing deformation with no further increase in stress. (5)

plastic limit: (a) The water content corresponding to an arbitrary limit between the plastic and the semisolid states of consistency of a soil. (b) Water content at which a soil will just begin to crumble when rolled into a thread approximately 1/8 in. (3.2 mm) in diameter. (5)

plasticity: The property of a soil or rock which allows it to be deformed beyond the point of recovery without cracking or appreciable volume change. (5)

plasticity range: The range of moisture weight percentage within which a small sample of soil exhibits plastic properties. (1)

pore-size distribution: The volume of the various sizes of pores in a soil. Expressed as percentages of the bulk volume (soil plus pore space). (1)

porosity: The ratio, usually expressed as a percentage, of: (a) The volume of voids of a given soil or rock mass, to (b) The total volume of the soil or rock mass. (5)

potential, soil water: See soil water.

preconsolidation pressure (prestress): The greatest effective pressure to which a soil has been subjected. (5)

pressure surface: The level of the water surface in an (imaginary) vertical well connecting with an aquifer. (5)

pressure-void ratio curve (compression curve): A curve representing the relationship between effective pressure and void ratio of a soil as obtained from a consolidation test. The curve has a characteristic shape when plotted on semilog paper with pressure on the log scale. The various parts of the curve and extensions to the parts have been designated as recompression, compression, virgin compression, expansion, rebound, and other descriptive names by various authorities. (5)

primary state of stress: The stress in a geological formation before it is disturbed by manmade works. (7)

principal stress (strain): The stress (strain) normal to one of three mutually perpendicular planes on which the shear stresses (strains) at a point in a body are zero. (7)

profile, soil: A vertical section of the soil through all its horizons and extending into the parent material. (1)

puddled soil: A soil in which structure has been mechanically destroyed, which allows the soil to run together when saturated with water. A soil that has been puddled occurs in a massive nonstructural state. (2)

pyroclastic: Pertaining to fragmental materials produced by usually explosive, aerial ejection of clastic particles from a volcanic vent. (3)

reaction, soil: The degree of acidity or alkalinity of a soil, usually expressed as a pH value. Descriptive terms commonly associated with certain ranges in pH are: extremely acid, less than 4.5; very strongly acid, 4.5 to 6.0; slightly acid, 6.1 to 6.5; neutral, 6.6 to 7.3; slightly alkaline, 7.4 to 7.8; moderately alkaline, 7.9 to 8.4; strongly alkaline, 8.5 to 9.0; and very strongly alkaline, greater than 9.1. (1)

recharge: Natural or artificial replenishment of an aquifer. (6)

regolith: All unconsolidated earth materials above the solid bedrock. (3)

relative consistency: Ratio of: (a) The liquid minus the natural water content, to (b) The plasticity index. (5)

relative density: The ratio of: (a) The difference between the void ratio of a cohesionless soil in the loosest state and any given void ratio, to (b) The difference between the void ratios in the loosest and the densest states. (5)

remolded soil: Soil that has had its natural structure modified by manipulation. (5)

residual shrinkage: The decrease in the bulk volume of soil in addition to that caused by the loss of water. (1)

residual stress: Stress remaining in a solid under zero external stress after some process that causes the dimensions of the various parts of the solid to be incompatible under zero stress; for example, (a) Deformation under the action of external stress when some parts of the body suffer permanent strain, or (b) Heating or cooling of a body in which the thermal expansion coefficient is not uniform throughout the body. (5)

retentivity profile, soil: A graph showing the retaining capacity of a soil as a function of depth. The retaining capacity may be for water, for water at any given tension, for cations, or for any other substances held by soils. (1)

rock: Natural solid mineral matter occurring in large masses or fragments. (5)

sand: (a) A soil particle between 0.05 and 2.0 mm in diameter. (b) Any one of five soil separates, namely: very coarse sand, coarse sand, medium sand, fine sand, and very fine sand. See soil separates. (c) A soil textural class. See soil texture. (1)

saturation: A condition reached by a material, whether it be in solid, gaseous, or liquid state, that holds another material within itself in a given state in an amount such that no more of such material can be held within it in the same state. The material is then said to be saturated on in a condition of saturation. (2)

sedimentation: The process of subsidence and deposition of suspended matter carried by water, wastewater, or other liquids, by gravity. It is usually accomplished by reducing the velocity of the liquid below the point at which it can transport the suspended material. (2)

seepage (percolation): The slow movement of gravitational water through the soil or rock. (5)

seepage force: The force transmitted to the soil or rock grains by seepage. (5)

sensitivity: Ratio of disturbed to undisturbed shear strength of a soil. (6)

shear failure (failure by rupture): Failure in which movement cause by shearing stresses in a soil or rock mass is of sufficient magnitude to destroy or seriously endanger a structure. (a) General shear failure: Failure in which the ultimate strength of the soil or rock is mobilized along the entire potential surface of sliding before the structure supported by the soil or rock is impaired by excessive movement. (b) Local shear failure: Failure in which the ultimate shearing strength of the soil or rock is mobilized only locally along the potential surface of sliding at the time the structure supported by the soil or rock is impaired by excessive movement. (5)

shear force: A force directed parallel to the surface element across which it acts. (7)

shear plane: A plane along which failure of material occurs by shearing. (7)

shear strain: The change in shape, expressed by the relative change of the right angles at the corner of what was in the undeformed state an infinitesimally small rectangle or cube. (7)

shear strength: The maximum resistance of a soil or rock to shearing stresses. (5)

shear stress: Stress directed parallel to the surface element across which it acts. (7)

shrinkage limit: The maximum water content at which a reduction in water content will not cause a decrease in volume of the soil mass. (5)

silt: (a) A soil separate consisting of particles between 0.005 and 0.002 mm in equivalent diameter. See soil separates. (b) A soil texture class. See soil texture. (1)

skeleton grains: The individual grains larger than colloidal size (> 0.002 mm) of a soil material; they consist of mineral grains originally present in the parent material and resistant siliceous and organic bodies. (4)

slickensides: Polished and grooved surfaces produced by one mass sliding past another. (1)

S-matrix: The material (plasma and/or skeleton grains and associated voids) within the simplest (primary) peds, or composing apedal soil materials that does not occur as pedalogical features other than plasma separations; it may be absent in some soil materials, for example those that consist entirely of pedological features. (4)

soil: (a) The unconsolidated mineral material on the immediate surface of the Earth that serves as a natural medium for the growth of land plants. (b) The unconsolidated mineral matter on the surface of the Earth that has been subjected to and influenced by genetic and environmental factors of: parent material, climate (including moisture and temperature effects), macro- and microorganisms, and topography, all acting over a period of time and producing a product, soil, that differs from the material from which it is derived in many physical, chemical, biological, and morphological properties and characteristics. (1)

soil air: The soil atmosphere; the gaseous phase of the soil, being that volume not occupied by solid or liquid. (1)

soil auger: A tool for boring into the soil and withdrawing a small sample for field or laboratory observation. Soil augers may be classified into several types as follows: (a) Those with worm-type bits, unenclosed; (b) Those with worm-type bits enclosed in a hollow cylinder; and (c) Those with a hollow cylinder with a cutting edge at the lower end. (1)

soil fabric: The physical constitution of a soil material as expressed by the spatial arrangement of the solid particles and associated voids. (4)

soil horizon: A layer of soil or soil material approximately parallel to the land surface and differing from adjacent genetically related layers in physical, chemical, and biological properties or characteristics such as color, structure, texture, consistency, kinds and numbers of organisms present, degree of acidity or alkalinity, etc. (1)

soil mechanics: The science dealing with all phenomena which affect the action of soil in a capacity in any way associated with engineering. (8)

soil mineral: (a) Any mineral that occurs as a part of or in the soil. (b) A natural inorganic compound with definite physical, chemical, and crystalline properties (within the limits of isomorphism), that occurs in the soil. (1)

soil moisture: Water contained in the soil. (1)

soil-moisture tension: See moisture tension (or pressure).

soil morphology: (a) The physical constitution, particularly the structural properties, of the soil profile as exhibited by the kinds, thickness, and arrangement of the horizons in the profile, and by the texture, structure, consistency, and the porosity of each horizon. (b) The structural characteristics of the soil or any of its parts. (1)

soil physics: The organized body of knowledge concerned with the physical characteristics of soil and with the methods employed in their determinations. (5)

soil piping or tunneling: Accelerated erosion which results in subterranean voids and tunnels. (1)

soil science: That science dealing with soils as a natural resource on the surface of the Earth including soil formation, classification, and mapping, and physical, chemical, biological, and fertility properties of soil per se; and these properties in relation to their management. (1)

soil separates: Mineral particles, < 2.0 mm in equivalent diameter, ranging between specified size limits. The names and size limits of separates recognized in the U.S.D.A. system are: very coarse sand, 2.0 to 1.0 mm; coarse sand, 1.0 to 0.5 mm; medium sand, 0.5 to 0.25 mm; fine sand, 0.25 to 0.10 mm; very fine sand, 0.10 to 0.05 mm; silt, 0.05 to 0.002 mm; and clay, < 0.002 mm. The U.S.C.S. particle and size range are as follows: coarse sand, 2.0 to 4.76 mm; medium sand, 0.42 to 2.0 mm; fine sand, 0.074 to 0.42 mm; fines (silt and clay), < 0.074 mm. (Note: U.S.C.S. silt and clay designations are determined by response of the soil to manipulation at various water contents rather than by measurement of size.)

soil series: The basic unit of U.S.D.A. soil classification being a subdivision of a family and consisting of soils which are essentially alike in all major profile characteristics except the texture of the A horizon. (1)

soil solution: The aqueous liquid phase of the soil and its solutes. (1)

soil structure: The combination or arrangement of primary soil particles into secondary particles, units, or peds. These secondary units may be, but usually are not, arranged in the profile in such a manner as to give a distinctive, characteristic pattern. The secondary units are characterized and classified on the basis of size, shape, and degree of distinctness into classes, types, and grades, respectively. (1)

soil suction: A measure of the force of water retention in unsaturated soil. Soil suction is equal to a force per unit area that must be exceeded by an externally applied suction to initiate water flow from the soil. Soil suction is expressed in standard pressure terms. (2)

soil texture: The relative proportion of the various soil separates in a soil as described by the classes of soil texture. (1)

soil water: A general term emphasizing the physical rather than the chemical properties and behavior of the soil solution.

A. TERMS RELATING TO THE STATE OF WATER IN SOIL:

Water in soil is subject to several force fields originating from: the presence of the soil solid phase; the dissolved salts; the action of external gas pressure; and, the gravitational field. These effects may be quantitatively expressed by assigning an individual component potential to each. The sum of these potentials is designated the total potential of soil water and may be identified with the partial specific Gibb's free energy of the soil water relative to free pure water at the same temperature. It should be noted that soil water is understood to be the equilibrium solution in the soil; pure water refers to the chemically pure compound HOH. (1)

capillary potential: The amount of work that must be done per unit of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water, identical in composition to the soil water, from a pool at the elevation and the external gas pressure of the point under consideration, to the soil water.

differential water capacity: The absolute value of the rate of change of water content with soil water pressure. The water capacity at a given water content will depend on the particular desorption or adsorption curve employed. Distinction should be made between volumetric and specific water capacity.

gas pressure potential: This potential component is to be considered only when external gas pressure differs from atmospheric pressure as, e.g., in a pressure membrane apparatus. A specific term and definition is not given.

gravitational potential: The amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water, identical in composition to the soil water, from a pool at a specified elevation and at atmospheric pressure, to a similar pool at the elevation of the point under consideration.

hydraulic head: The elevation with respect to a specified reference level at which water stands in a piezometer connected to the point in question in the soil. Its definition can be extended to soil above the water table if the piezometer is replaced by a tensiometer. The hydraulic head in systems under atmospheric pressure may be identified with a potential expressed in terms of the height of a water column. More specifically it can be identified with the sum of gravitational and capillary potentials, and may be termed the hydraulic potential.

osmotic potential: The amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water, at a specified elevation and at atmospheric pressure, to a pool of water identical in composition to the soil water (at the point under consideration), but in all other respects being identical to the reference pool.

osmotic pressure: The pressure to which a pool of water, identical in composition to the soil water, must be subjected in order to be in equilibrium, through a semipermeable membrane, with a pool of pure water (semipermeable means permeable only to water) . May be identified with the osmotic potential defined above.

soil water pressure: The pressure (positive or negative), relative to the external gas pressure on the soil water, to which a solution identical in composition to the soil water must be subjected in order to be in equilibrium through a porous permeable wall with the soil water. May be identified with the capillary potential defined above.

total potential (of soil water): The amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water, at a specified elevation and at atmospheric pressure, to the soil water (at the point under consideration). The total potential (of soil water) consists of the following:

total pressure: The pressure (positive or negative), relative to the external gas pressure on the soil water, to which a pool of pure water must be subjected in order to be in equilibrium through a semipermeable membrane with the soil water. Total pressure is thus equal to the sum of soil water pressure and osmotic pressure. Total pressure may also be derived from the measurement of the partial pressure of the water vapor in equilibrium with the soil water. May be identified with the total potential defined above when gravitational and external gas pressure potentials can be neglected.

water content: The amount of water lost from the soil upon drying to constant weight at 105 degrees Centigrade; expressed either as the weight of water per unit weight of dry soil or as the volume of water per unit bulk volume of soil. The relationships between water content and soil water pressure can be referred to as the soil moisture characteristic curve. Depending upon whether the curve is determined with decreasing or increasing water content one may designate it as a desorption or adsorption curve, respectively.

B. TERMS RELATING TO THE MOVEMENT OF WATER IN SOIL

Experimentally it has been established that generally the flow of a fluid in a porous medium can be described by Darcy's law which states that the flux of fluid is proportional to the driving force. In viscous flow of water in soils, the driving force equals the negative gradient of the hydraulic potential. (1)

hydraulic conductivity: The proportionality factor in Darcy's law as applied to the viscous flow of water in soil, i.e., the flux of water per unit gradient of hydraulic potential. For the purpose of solving the partial differential equation of the non-steady-state flow in unsaturated soil it is often convenient to introduce a variable termed the soil water diffusivity.

soil water diffusivity: The hydraulic conductivity divided by the differential water capacity (care being taken to be consistent with units), or the flux of water per unit gradient of moisture content in the absence of other force fields.

specific gravity (of solids): Ratio of: (a) The weight in air of a given volume of solids at a stated temperature, to (b) The weight in air of an equal volume of distilled water at a stated temperature. (1)

specific retention: Ratio of volume of suspended water to volume of associated voids. (6)

specific surface: The surface area per unit of volume of soil particles. (5)

specific yield: Ratio of voids not occupied by suspended water to the total volume of the associated area. (6)

stability: The condition of a structure or a mass of material when it is able to support the applied stress for a long time without suffering any significant deformation or movement that is not reversed by the release of stress. (7)

Standard Penetration Test (SPT): The most commonly used in situ test to measure in relative terms the resistance of soil to deformation by shearing. (6)

strain (linear or normal): The change in length per unit of length in a given direction. (5)

stratified: Arranged in strata, or layers. The term refers to geologic material. Layers in soils that result from the processes of soil formation are called horizons; those inherited from the parent material are called strata. (3)

strength: Maximum stress which a material can resist without failing for any given type of loading. (7)

stress: The force per unit area acting within the soil mass. (5)

structure: One of the larger features of a rock mass, like bedding, foliation, jointing, cleavage, or brecciation; also the sum total of such features as contrasted with texture. Also, in a broader sense, it refers to the structural features of an area such as anticlines or synclines. (7) See also soil structure.

susbsidence: The downward displacement of the overburden (rock or soil, or both) lying above an underground excavation or adjoining a surface excavation. Also the sinking of a part of the earth's crust. (7)

subsoil: In general concept, that part of the soil below the depth of plowing. (2)

summation curve, particle size: A curve showing the accumulative percentage by weight of particles within increasing (or decreasing) size limits as a function of diameter; the percent by weight of each size fraction is plotted accumulatively on the ordinate as a function of the total range of diameter represented in the sample plotted on the abscissa. (1)

surface sealing: The orientation and packing of dispersed soil particles in the immediate surface layer of the soil, rendering it relatively impermeable to water. (1)

swelling pressure: Pressure exerted by confined swelling clays when moisture content is increased. (6)

tensile strength (unconfined or uniaxial tensile strength): The load per unit area at which an unconfined cylindrical specimen will fail in a simple tension (pull) test. (5)

tensiometer: A device for measuring the negative pressure (or tension) of water in soil in situ; a porous, permeable ceramic cup connected through a tube to a manometer or vacuum gauge. (1)

tension, soil water: The expression, in positive terms, of the negative hydraulic pressure of soil water. (2)

transmissivity: Rate of transmission of water through unit width of an aquifer under unit hydraulic gradient. (6)

transpiration: Water loss from leaves and other plant organs to the atmosphere. (6)

triaxial compression: Compression caused by the application of normal stresses in three perpendicular directions. (7)

triaxial shear test (triaxial compression test): A test in which a cylndrical specimen of soil or rock encased in an impervious membrane is subjected to a confining pressure and then loaded axially to failure. (5)

triaxial state of stress: State of stress in which none of the three principal stresses is zero. (5)

tuff: Volcanic ash usually more or less stratified and in various states of consolidation. (1)

ultimate bearing capacity: The average load per unit of area required to produce failure by rupture of a supporting soil or rock mass. (5)

unconsolidated-undrained test (quick test): A soil test in which the water content of the test specimen remains practically unchanged during the application of the confining pressure and the additional axial (or shearing) force. (5)

undisturbed sample: A soil sample that has been obtained by methods in which every precaution has been taken to minimize disturbance to the sample. (5)

uniaxial (unconfined) compression: Compression caused by the application of normal stress in a single direction. (7)

uplift: The hydrostatic force of water exerted on or underneath a structure, tending to cause a displacement of the structure. (7)

unsaturated flow: The movement of water in a soil which is not filled to capacity with water. (1)

vane shear test: An in-place shear test in which a rod with thin radial vanes at the end is forced into the soil and the resistance to rotation of the rod is determined. (5)

vapor pressure: (a) The pressure exerted by a vapor in a confined space. It is a function of the temperature. (b) The partial pressure of water vapor in the atmosphere. (c) Partial pressure of any liquid. (2)

viscosity: The cohesive force existing between particles of a fluid which causes the fluid to offer resistance to a relative sliding motion between particles. (2)

voids: Entities which are interconnected with each other either through voids of dissimilar size and shape, through narrow necks, or through intersection with voids of similar size and shape. (4)

void ratio: The ratio of: (a) The volume of void space, to (b) The volume of solid particles in a given soil mass. (5)

volumetric shrinkage (volumetric change): The decrease in volume, expressed as a percentage of the soil mass when dried, of a soil mass when the water content is reduced from a given percentage to the shrinkage limit. (5)

water-holding capacity: The smallest value to which the water content of a soil or rock can be reduced by gravity drainage. (5)

water-retention curve: See moisture-retention curve.

water table: The upper surface of ground water or that level below which the soil is saturated with water; locus of points in soil water at which the hydraulic pressure is equal to atmospheric pressure. (1)

weathering: All physical and chemical changes produced in rocks, at or near the earth's surface, by atmospheric agents. (1)

yield stress: The stress beyond which the induced deformation is not fully annulled after complete destressing. (7)

zero air voids curve (saturation curve): The curve showing the zero air voids unit weight as a function of water content. (1)

zone of aeration: That part of the ground in which the voids are not continuously saturated. (1)

zone of saturation: That part of the ground in which the voids are continuously saturated. (1)

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